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Developing a wastewater lifecycle management framework for onshore gas development in the Northern Territory

Project W24 Final Report

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Photo credit: McArthur Basin Exploration (Santos, 2019a)

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Abbreviations

AHP	Analytical Hierarchy Process
BOD	biochemical oxygen demand (BOD)
BTEX	benzene, toluene, ethylbenzene and xylene
COD	chemical oxygen demand
CoP	Code of Practice
CSG	coal seam gas
DENR	Department of Environment and Natural Resources, NT
DPIR	Department of Primary Industry and Resources, NT
EC	electrical conductivity
ED	electrodialysis
EDR	electrodialysis reversal
EMP	Environmental Management Plans
FO	forward osmosis
FTE	freeze-thaw evaporation
HF	hydraulic fracturing
KPI	key performance indicator
LGA	Local Government Area
MCDA	Multiple criteria decision-making analysis
MED	multi-effect distillation
MF	microfiltration
ML	megalitre
MPPE	macro-porous polymer extraction
MSF	multistage flash
MVC	mechanical vapour compression
NORM	naturally occurring radioactive materials
NT	Northern Territory
RO	reverse osmosis
RRAC	Regional Research Advisory Committee
SAR	Sodium adsorption ratio
TDS	total dissolved solids
TPH	total petroleum hydrocarbons
UF	ultrafiltration
UOG	unconventional oil and gas
VOC	volatile organic compounds
WWMP	wastewater management plan

Executive Summary

The Beetaloo Basin contains an estimated gas resource of 178,200 petajoules (PJ). Shale gas development is imminent in the Northern Territory (NT), and currently in the exploration phase. Since 2010, around 70 exploration and production wells have been drilled onshore in the NT and exploration seismic data have been acquired in the McArthur, Amadeus, Pedirka and Georgina Basins. There are currently 37 granted exploration licences for petroleum in the onshore NT.

The need for an economical and environmentally sustainable approach for managing arising wastewater is critical, given the large volumes that are expected to be generated in the coming years in the Beetaloo region as the industry moves from exploration to the production phase. The Scientific Inquiry into Hydraulic Fracturing in the NT identified water concerns were a high priority for the community. The Inquiry recommended that a wastewater management framework be developed, route tracking during transport, and no reinjection of treated or untreated wastewater. The Inquiry also prohibited discharge of wastewater, whether treated or untreated, to drainage lines, waterways, temporary stream systems or waterholes. Managing wastewater within these constraints provides an opportunity for novel solutions.

Internationally, there are examples of effective treatment and reuse, and decision frameworks on how to arrive at such options, however there are gaps in understanding the specific NT context, and optimisation of wastewater treatment to achieve broader social, environmental and economic objectives. This project sought to review the water qualities arising from specific NT shales, the proximity to industries for beneficial reuse, and develop a framework to optimise the options space for treatment and beneficial reuse relevant to the specific environmental and economic context of the NT.

The project has identified approaches to closed loop water cycle management for shale gas operations in the NT to optimise for environmental, social and economic objectives. These objectives were co-created by industry, government and community stakeholders during the project, and supported by relevant guidelines. The approach was technology agnostic, and does not prescribe particular technology choices, but rather a range of possibilities informed by key environmental, social and economic indicators.

Researchers have identified the water quantities and qualities likely at each stage of the production process; identified process, treatment or offtake opportunities to reduce environmental impacts; and developed a framework for identifying and maximising beneficial use and reuse opportunities and reducing costs and potential risks of environmental harm from wastewater. The project assessed and compared water quality with data from NT test wells, reviewed water use options and incorporated them into a NT framework for management, reuse and treatment of onshore gas wastewaters.

We developed an MCDA (Multi-Criteria Decision Analysis) framework which applies a holistic approach incorporating technical, environmental and economic analysis with the consideration of balancing community, social benefits and outcomes. Various options were analysed against the KPIs and beneficial use and optimisation criteria requirements to develop decision support for wastewater management.

The initial scope of the project was to include application of MCDA for all stages of the development life cycle in the Beetaloo. During industry and government consultation combined with assessment of available data during the design phase of the MCDA, it was determined that the early stage of industry development in the NT would constrain this approach. Data was available on the three wells in the appraisal stages. High variability in water quality and flow data also meant that there is still considerable uncertainty regarding the quantities, qualities and locations likely for wastewater production. These have limited the ability to apply the full wastewater framework to broadly optimise the operational, environmental, economic and social criteria across the project life cycle.

For this reason we applied MCDA to water treatment only. MCDA treatment modules developed and applied for the exploration phase found evaporation ponds a feasible method for disposing of small amounts of wastewater. Nevertheless, this treatment option is associated with a low environmental score. Evaporation ponds are widely used currently during exploration and appraisal stage due to operational convenience. At later stages of development these will be cost and size prohibitive and will have a range of downsides to their use which make them unviable.

In the Beetaloo Sub-Basin, trucking wastewater for disposal may not be a viable option in later phases of development as the cost of transportation will be too high for production volumes. Suitable disposal sites, regulations, road infrastructure limitations, or community concerns may also limit the transportation to distant treatment as an option. In these cases, other disposal options, such as on-site treatment and reuse, may be more viable alternatives. Current relevant NT regulations and policies define how shale wastewaters be treated and contained, but do not present options for managing water used in shale gas operations.

Current disposal cost estimates at Jackson facility range from $0.10 to $0.95 per litre ($950/m^3), depending on the total dissolved solids (TDS) levels, and this cost does not include transportation costs. Whereas operating expenses for alternative treatment options range from $2 to $60 per cubic meter of feed. To minimise the environmental impact of wastewaters from hydraulic fracturing in shale gas production, a combination of pre-treatment techniques, evaporation ponds for disposal of highly saline wastewaters, and new desalination technologies may be necessary. In the Katherine and wider Beetaloo basin region, there are various potential mining, construction, and agricultural uses for appropriately treated reuse water. Additionally, there may be further opportunities for industrial reuse in Darwin, particularly in chemical industries, that warrants further investigation. Centralised treatment facilities may introduce economies of scale and provide regional employment and economic activity. When there are a greater number of wells appraised and the water qualities and volumes are better understood, a fuller assessment and use of this MCDA tool to ascertain optimal solutions will be possible.

“Fit-for-purpose treatment” is required to enhance cost-effective regulatory compliance, water recovery and reuse, and resource valorisation. It can range from minimum effective treatment for reuse as fracture fluid, to crop irrigation using advanced treatment technologies.

With shale gas expected to maintain a significant role in energy systems for decades to come, new strategies will be crucial to minimise environmental and social impacts. While water reuse is an ongoing challenge for the shale gas industry, it is being actively explored and is likely to be important in the Australian shale gas sector.

1 Objectives

This project sought to:

- Develop an options framework and decision criteria for water and wastewater management for Northern Territory (NT) onshore shale gas development
- Base the framework on sustainable water management principles and informed by community concerns identified through the Pepper Inquiry
- Engage with industry, government and community stakeholders to inform the approach and ensure suitability to assist industry and regulators to effectively and efficiently manage wastewater for potentially broader benefits to society and community
- Identify and parameterise key performance indicators for a range of social, environmental and economic assessment criteria
- Explore the current and potential future options for safe disposal of wastewater, thereby seeking to address key wastewater recommendations of the NT Pepper Inquiry (recommendations 5.5, 7.9 and 7.17).
- Review, in consultation with industry, potential treatment technologies and determine the feasibility of their practical implementation, and features important to their adoption by industry
- Develop two case studies in the Beetaloo Basin, NT to test the utility and efficacy of the approach.

2 Background

2.1 Australian and Northern Territory context

A major community concern regarding development of shale gas is water management (Cook et al., 2013; Pepper et al., 2018). The NT Hydraulic Fracturing Inquiry identified key concerns about wastewater for a shale gas and oil industry in the Northern Territory. The Inquiry recommended the prohibition of discharge of wastewaters to surface waters and reinjection of wastewater at depth into shale formations (Pepper et al., 2018). Recommendation 5.5 put forward that a framework for the management of wastewater be developed by government in consultation with industry and community. While the Code of Practice for Petroleum Activities in the Northern Territory partly addresses this recommendation by providing the objectives and minimum standards for a wastewater management framework, it does not present options for managing water used in shale gas and oil operations, or suggest options that may become available as the industry develops. In addition, two other HF Recommendations (recommendations 7.9 and 7.17) place specific limitations on disposal options for shale gas hydraulic fracturing wastewater. In the NT, regulation requires that individual project Environmental Management Plans (EMPs) require wastewater management plans specific to single tenements or company developments. However, there is no industry-wide solution or approach to address wastewater management at scale. While the quantities of flowback and produced water in shale gas developments are far less than those in coal seam gas (CSG) developments, there are wastewater management lessons from the Queensland experience (Cook et al., 2013; Huddlestone-Holmes et al., 2018). Brine volumes are a considerable challenge given the widespread adoption of reverse osmosis as the main treatment option for CSG production waste waters. Optimal planning and management of NT shale gas water based on agreed objectives has the potential to contribute to decreased management challenges and environmental impacts and alleviate community concerns. Such management will reduce the volumes of water required (through reuse and recycling), minimise potential pollutants (through industrial ecology/waste to resource options) and incorporate appropriate treatment technologies and disposal options for wastewater.

2.2 Water use in shale gas development

There are three main sources of wastewater produced during shale gas extraction: well drilling muds, flowback water and produced water. Other ancillary uses of water for site management such as dust suppression are relatively insignificant. Well drilling muds provide lubrication and cooling to the drill bit and represent the lowest volume of wastewater generated during well development (typically 1-2 ML per well) (Pepper et al., 2018). Well drilling muds are typically contained in lined sedimentation pits, where the clarified saline water is removed for treatment and the mud can be recycled for use in further drilling (Huddlestone-Holmes et al., 2018). Drill cuttings will be of the order of 150 to 200 m^3 for a 3,000 m well interval with a 2,000 m lateral extension drilled using rotary mud drilling methods (Huddlestone-Holmes et al., 2018). In the NT, management of wastewater (including drill cuttings) from unconventional gas is similar to many other mining and industrial processes, although treatment of produced water may vary (Hawke, 2014).

During operations, shale gas wells consume water from local sources and generate flowback and produced water. Well development requires water, to which additives are mixed to form hydraulic fracturing fluid. The resulting fluid is then injected deep into the target shale formation to stimulate gas flow. In the NT, water for fracturing fluids will be sourced from groundwater, unless it can be obtained and recycled from other uses and users, as use of surface water is prohibited. Consultation during the 2018 Scientific Inquiry into Hydraulic Fracturing in the NT showed that the community want the industry to use lower quality water than that used by others (such as for stock and domestic) (Pepper et al., 2018).

Flowback water (return of the hydraulic fracturing fluid injected into the well back to the surface) contains both the chemical additives from the hydraulic fracturing fluid, and the native chemistries present deep in the shale formations. Shale formations can yield flowback water that is saline. The flowback water may contain ions such as barium, strontium and bromine; low concentrations of heavy metals; organic matter; and naturally occurring radioactive materials (NORM) from the rock and formation water (Cook et al., 2013; Huddlestone-Holmes et al., 2018). The final chemistries and volumes of flowback and produced waters are highly dependent on the local geologies in the target formation and other localised conditions. Cook et al. (2013) estimated that between 25% and 75% of the volume injected during hydraulic fracturing returns to the surface, with the initial chemistry reflecting the hydraulic fracturing fluid. Over time the target formations affect the chemistry. Flowback and produced water are often reinjected at depth as a disposal method in other countries and regions, but in the NT this method of disposal is prohibited. Plans are required to be developed to best treat and reuse the water where possible, and until ultimate treatment and disposal, wastewater must be stored in closed tanks (Pepper et al., 2018).

Produced water is formation water that is released during the fracture stimulation at depth and returns to the surface through the gas extraction process. Produced water, by its nature, reflects the chemistry of target formations, and may include barium, strontium, bromine, heavy metals, organic matter and NORM. The relative quantity of produced water to flowback water is quite low in shale gas resources. For a 6000-well development, a cumulative total of 45,600ML of flowback water and 1,710ML per year of produced water might be expected over the life of a project (Cook et al., 2013; Huddlestone-Holmes et al., 2018). Depending on development size, flowback and produced waters in shale gas can be stored onsite (in closed tanks in the NT) before being piped to onsite treatment constructed for the purpose or transported by tanker to regional water treatment facilities (Huddlestone-Holmes et al., 2018).

Produced water for shale gas wells is likely to contain increased levels of contaminants and potentially regulated wastes. Therefore, it needs higher levels of water treatment. Wastewater storage capacity and onsite treatment are likely to be significantly less than for CSG.

The volume of water used in shale gas developments is in the order of 5 to 20 megalitres (ML) per well, and is likely to vary depending on local conditions (Cook et al., 2013; Council of Canadian Academies, 2014; King, 2012). At a scale of a 1000-well shale gas development, up to 20,000 ML would be required (Huddlestone-Holmes et al., 2018). While this volume of water is not large compared to other water users, such as agriculture, local impacts at catchment or aquifer scale may need to be carefully managed (Hawke, 2014). Competition with other water users could be reduced if some recycled or saline water were used (Council of Canadian Academies, 2014).

The quantities and qualities of flowback water and produced water likely to be generated for shale gas and oil development in the NT is highly uncertain, and dependent on local geologies and extraction methods.

2.3 Water use through the project lifecycle

The life cycle of unconventional oil and gas (UOG) development can be summarised as four stages: predrilling construction, drilling, hydraulic fracturing, and ongoing production (Figure 1). The water used in UOG production can be categorised further as direct, indirect, or ancillary use. Direct water use is defined as the water used for drilling and hydraulic fracturing a well and for maintaining the well during ongoing production. Indirect water use is the water used at or near a well pad. The water used for dust abatement is also considered an indirect use but may be applied away from the well pad. Ancillary water use is the additional local or regional water use resulting from a change (for example, population) directly related to UOG development throughout the life cycle that is not used directly in the well or indirectly for any other purpose at the well pad.

Of the four stages in the life cycle, drilling, hydraulic fracturing, and ongoing production involve direct water use. The drilling stage includes water used directly in drilling the well and cementing the casing. The hydraulic fracturing stage includes water used directly for mixing the hydraulic fracturing fluid and injecting into the well. The ongoing production stage includes water used directly for maintaining the well, such as descaling the casing, and for potentially refracturing the well.

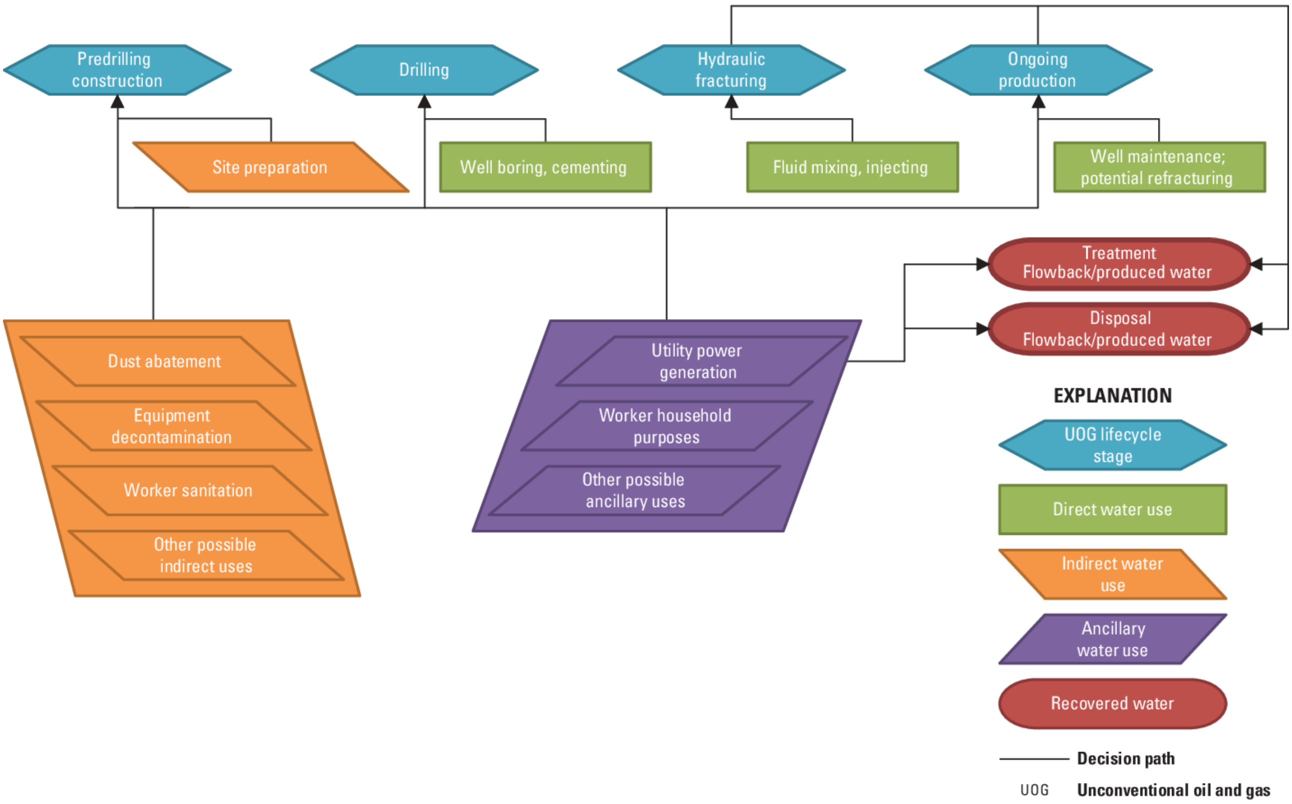


Figure 1. Direct, indirect, and ancillary water uses associated with the life cycle of unconventional oil and gas development. (Valder et al., 2018)

2.4 Challenges in shale gas water management

The NT HF Inquiry found that shale gas production remains controversial in the NT due in part to concerns over impacts associated with the storage, transport, and disposal of fluids that return to the surface during hydraulic fracturing (Pepper et al., 2018). At this early stage of the industry in the NT, shale gas wastewater management consists of local storage of HF wastewaters, evaporation to reduce volumes and the transport of the remaining liquid wastes to treatment and disposal facilities in Queensland (Origin Energy, 2019b; Santos, 2019a). The nearest wastewater treatment facility is over 2400 km away in Jackson, western Queensland, and requires considerable risk management and controls along regional transport routes to manage spill risks. Transport is a significant cost to industry. Decisions on disposal of the residual flowback and produced waters for future stages of the industry are yet to be made, pending results of well testing during the current appraisal stages (Origin Energy, 2019b; Santos, 2019a). These inevitable logistical and economic challenges will continue to escalate as the industry expands. If decisions at future stages of development are made based on advice of wastewater disposal service providers, there is the risk that only a narrow range of options will be considered. Industry estimates that there are likely to be 1,000-1,150 wells on 104 -140 drilling pads in the Beetaloo, using 2,500-5,000 ML of water per year (Pepper et al., 2018). Wastewater management practices are often largely driven by the economics and logistics of disposal options. However, with shale gas expected to maintain a significant role in our energy systems for decades to come, new strategies will be crucial to minimise environmental and social impacts.

A challenge associated with the wastewater produced in coal seam gas extraction has been high salinity usually found in these liquid effluents, especially in produced water, with TDS concentration increasing after the fracturing operation (Figure 2). The approach largely adopted in Queensland has been to use reverse osmosis (RO) with a number of preceding steps to remove key contaminants. This results in large volumes of brine or further processing to dry salt product, which then requires sale or disposal depending on quality and composition.

Managing increasing quantities of high-salinity produced waters containing hydrocarbons, sometimes NORM, and other organic and inorganic compounds within regulatory constraints will be a critical challenge as wastewater volumes threaten to overwhelm the limited infrastructure, or become cost prohibitive for transport and treatment interstate. The rapid generation of large volumes of water makes flowback waters amenable to reuse in subsequent wells or frac sites. However, the produced waters that constitute the majority of total wastewater production are typically not reused due to logistical challenges associated with storing and transporting incremental and variable wastewater volumes. Produced fluid reuse may also be precluded by inadequate water quality, such as excessive TDS or divalent cations that promote scale formation. As produced fluids will increasingly dominate future wastewater flows with declining well completions, and are generated more intermittently as wells age, strategic planning is needed to manage variable wastewater qualities and quantities with minimal environmental impacts.

In multi-well pad operations overseas, there is a growing practice to re-use flowback and produced waters in subsequent hydraulic fracturing operations in what is known as 'internal reuse' (Pepper et al., 2018). The internal reuse minimises the wastewater environmental impact and treatment costs while reducing the need for fresh water as fracturing fluid. Conversely, the accumulation of high concentrations of dissolved solids can create operational problems.

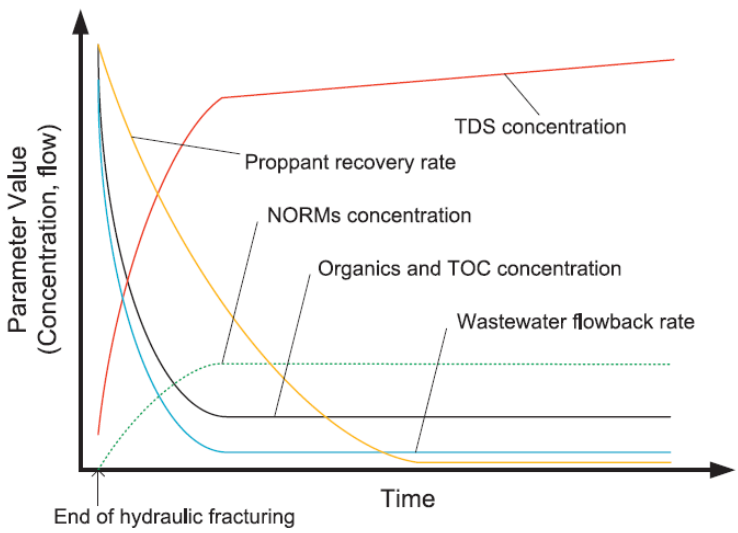


Figure 2. Conceptual profiles of different parameters associated with wastewater production after hydraulic operations (adapted from Estrada and Bhamidimarri (2016)). (Proppant is a solid material, typically sand, treated sand or human-made ceramic materials, designed to keep an induced hydraulic fracture open, during or following a fracturing treatment.)

Due to the infancy of the shale gas industry in the NT, the project team used data from the few available Environmental Management Plans (EMPs), worked with industry and regulators to review company data on exploration and test well waters, and studied national and international literature relevant to the NT.

The project investigated current and likely potential future practices through literature review and surveys of industry representatives, regulators and community in the NT. The project also examined related or potentially symbiotic industries that may have similar treatment needs to shale gas or potential or symbiotic feedwater needs. The project also assessed centralisation or decentralisation of treatment approaches at various stages of the industry to ascertain if these are likely candidates for optimisation of wastewater management.

2.5 Sustainable wastewater management

There are few examples of optimisation of wastewater for sustainability outcomes in the shale gas industry despite over 60 years of global operations. Business-as-usual treatment of wastewaters produced in the shale gas production process poses a challenge for the development of the shale gas industry, given the Pepper Inquiry recommendations and high community expectations (Pepper et al., 2018).

There is increasing research on innovative solutions to the challenges posed by wastewater generated from shales. Although most of the approaches are at early stages of development (mainly laboratory scale), they must be assessed for their potential for use in Australia.

Geza et al. (2018) have identified decision support tools for this process in well-established shales industries in the US. The treatment of water produced during shale gas production includes separating oil and water, removing suspended solids and organic compounds including NORM, and reducing the TDS. Selection of the technology for produced/flowback wastewater treatment will ultimately depend on the effluent properties and pollutants considered as well as the volume of wastewater to be treated in a single unit.

Membrane-based technologies, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), RO, FO, and MD have been the focus of recent research to develop new treatment approaches (Chang et al., 2019; Sun et al., 2019). The modular nature of these technologies makes them suitable for application to the varying wastewater quality and quantity encountered during treatment. The treatment technologies have different working principles, advantages, and limitations, particularly energy consumption, salinity limit, and water product quality. The project team has evaluated various potential treatment technologies and assessed their practical implementation feasibility. They have also identified key features that are crucial for industry adoption.

2.6 Wastewater treatment and reuse challenges

The rapid generation of large volumes of water makes flowback waters amenable to reuse in subsequent wells or frac sites. During the exploration phase, evaporation ponds have been used as a cost-effective method of disposing of highly saline wastewaters when compared to reuse. In multi-well pad operations overseas, there is a growing practice to re-use flowback and produced waters in subsequent hydraulic fracturing operations in what is known as ‘internal reuse’ (Pepper et al., 2018). The internal reuse minimises the wastewater environmental impact and treatment costs while reducing the need for freshwater as fracturing fluid. However, accumulation of high concentrations of dissolved solids can lead to operational problems.

Reuse of flowback water as drilling and hydraulic fracturing fluids for other wells is a desirable outcome because it would reduce the required volumes of water. However, a major problem with reuse of flowback water is the high concentrations of barium, calcium, iron, magnesium, manganese and strontium that can form scale (Kargbo et al., 2010). These constituents readily form precipitates, which can rapidly block the fractures in gas-bearing formations. Naturally occurring radioactive materials (NORM) may also become concentrated as water is reused. These aspects mean that some form of water treatment will be required.

The reuse of wastewater for off-site, non-oilfield operations can entail many technical, regulatory, economic, environmental and social considerations as summarised in Figure 3. Infrastructure costs, financing and planning are barriers for off-site use wastewater. Lack of nearby economically viable users also hinders wastewater reuse. Treatment technology to achieve a suitable end use may not exist or may be cost-prohibitive. Physical limitations to the installation of equipment, lack of storage capacity or conveyance pipelines, and compatibility with existing infrastructure may also hinder reuse options.

Figure 3. Challenges to reuse wastewaters (IPIECA, 2020)

Managing increasing quantities of high-salinity wastewater containing contaminants such as hydrocarbons, sometimes NORM, and other organic and inorganic compounds within regulatory constraints will be a critical challenge as wastewater volumes threaten to overwhelm the limited infrastructure or become cost-prohibitive in the case of transport and treatment interstate. Industry estimates between 1,000-1,150 wells on 104-140 drilling pads in the Beetaloo are likely to use 2,500-5,000 ML of water per year (Pepper et al., 2018). While water reuse is an ongoing challenge for the shale gas industry, the issue is being actively explored and is likely to be important in the Australian shale gas and oil sector (Cook et al., 2013; Hawke, 2014).

3 Method

The project was conducted in four stages.

Stage 1 – Industry, technology and stakeholder scan

- Local industry water qualities and wastewaters, technology options and stakeholder needs were investigated, and set the context for the research.
- A review was conducted of the existing water qualities and technology use across other shale gas areas in Australia and overseas, of innovative examples of sustainable and holistic water treatment approaches, and of regulations that apply to NT. EMPs have been approved and are published on NT government webpage (Government of Northern Territory, 2022) were reviewed for wastewater quality and treatment plans.
- A desktop scan of current and future industries in the NT was conducted to identify any potential likely beneficial reuse options.
- A stakeholder analysis was conducted and an engagement plan developed. A stakeholder survey was designed and completed and results compiled (Ethics approval number #198-20). The stakeholder engagement was conducted with industry and government through workshops, one-on-one discussions and surveys provided baseline data on current practices, and reported back to RRAC (Regional Research Advisory Committee) members for input.

Stage 2 – Options analysis and decision framework development

- Wastewater KPIs were developed for optimisation assessment, and stakeholder feedback obtained on draft criteria (mixed or segmented by stakeholder group – regulator and proponents) and the KPIs linked with code of practices.
- Potential treatment options were reviewed against the KPIs for addressing any knowledge gaps and completing optimisation criteria. This was to ensure the contributions to KPIs by key stakeholders in industry and government.
- A MCDA framework tool was developed by applying a holistic approach incorporating technical, environmental and economic analysis with the consideration of balancing community, social benefits and outcomes.
- The options were analysed against the KPIs and beneficial use and optimisation criteria requirements to develop decision support for wastewater management. The criteria weights were derived using the AHP approach. The identified treatment options and wastewater reuse criteria were aggregated.
- The MCDA includes a set of collective evaluation runs using different weighted criteria based on different prioritised options. This report compares the performance of treatment and reuse options. The project used results from the literature review and technical

assessment of treatment technologies to develop the decision tool based on multicriteria analysis.

Stage 3 – Fit for purpose wastewater case studies

- Compared the wastewater volume and quality data generated at different sites during exploration phase.
- Reviewed pros and cons of offsite wastewater trucking and its viability as industry moved into development phase.
- Compared wastewater chemical concentrations against benchmarks to explore various reuse options considering realistic site-specific data.
- Reviewed beneficial reuse potential of treated water by other industries in NT through conducting scan of agriculture and mining industries in the region.
- Applied the MCDA tool developed in this project to test the reuse readiness of each technology.
- Proposed a fit for purpose framework on the assumptions, and future projections such as well numbers, wastewater quality and quantity and disposal availability.

Stage 4 – Synthesise and finalise framework.

- Development and delivery of final report including writing up the final decision framework and case studies.

4 Industry, technology and stakeholder scan

4.1 Regulatory frameworks and codes

A range of regulatory frameworks and codes govern the management of shale gas wastewaters in the Northern Territory.

4.1.1 Petroleum Act 2016 (NT) and environment regulations

The Petroleum Act 2016 (NT) is the governing legislation for onshore petroleum activities in the NT. The Petroleum (Environment) Regulations (the Regulations) govern environmental management. The objectives of the Regulations are to ensure that:

1. Onshore oil and gas activities are carried out in a manner consistent with the principles of ecologically sustainable development
2. Environmental impacts and risks associated with onshore oil and gas activities are reduced to a level that is as low as reasonably practicable and acceptable.

To attain these objectives, the Regulations mandate that stakeholders must have an approved Environmental Management Plan (EMP) before undertaking a 'regulated activity'. The Regulations achieve these objectives by requiring interest holders to have an approved EMP in place before a 'regulated activity' can be undertaken. An EMP will be approved when the Minister is satisfied that approval criteria have been met. Under the Regulations, interest holders in petroleum titles must prepare and submit an EMP. It is essential to have an approved EMP for any activity that carries an environmental risk or impact and is just one of the numerous approvals needed for the undertaking to proceed. The approved EMP is a legal document that is binding and enforceable.

4.1.2 NT Hydraulic Fracturing (HF) Inquiry Recommendations

The scientific inquiry into hydraulic fracturing of onshore unconventional reservoirs in the NT set out to identify and assess the environmental, social, cultural and economic risks associated with hydraulic fracturing (Pepper et al., 2018). The inquiry identified the following potential water risks:

1. unsustainable groundwater use
2. contamination of groundwater from leaky wells
3. contamination of groundwater by surface spills of fracturing fluid chemicals (transit or storage) and wastewater
4. effects on surface or groundwater-dependent ecosystems.

The independent inquiry presented its final report to the NT Government in 2018. The report provides recommendations to mitigate to acceptable levels the identified risks associated with any onshore shale gas development in the NT, if the Government lifts the moratorium.

Releasing the report, the Chair of the inquiry, Justice Rachel Pepper, stated 'No industry is without risk, and any onshore shale gas industry is no exception. However, it is the Panel's opinion, expressed in the Final Report, that if all of the recommendations are implemented, the identified risks associated with any onshore shale gas industry can be mitigated or reduced to an acceptable level, and in some cases, the risks can be eliminated' (Government of Northern Territory, 2018).

Three key HF Recommendations place specific limitations on disposal options for shale gas hydraulic fracturing wastewater. Recommendation 5.15 requires that a framework for the management of wastewater be developed by government in consultation with industry and community. Recommendation 7.9 prohibits reinjection of wastewater until greater scientific investigations can define effective risk mitigations. Recommendation 7.17 further prohibits wastewater discharge from shale gas operations to any surface water systems, irrespective of treatment.

4.1.3 The Code of Practice for Onshore Petroleum Activities in the Northern Territory (Government of Northern Territory, 2019)

The Code of Practice (CoP) outlines requirements for the management of produced water or flowback fluid, including the development of a wastewater management plan (WWMP) (Government of Northern Territory, 2019). This Code applies to all petroleum well types including exploration, appraisal, development, monitoring, injection and production wells. The Code primarily addresses the management of environmental risks and environmental impacts associated with the conduct of regulated activities, along with the safety and operational risks associated with the environmental risks and environmental impacts.

According to the code, the required components of the WWMP framework include:

- Estimate of the quantities and quality of water and wastewater from the petroleum activity
- Definition of the methods and approaches that will be used to store, treat, and reuse water and ultimately dispose of wastewater, including the activities will be undertaken at the site of the approved petroleum activity
- Estimation of the quantities and quality of wastewater, or wastewater derived solids that will be removed from the petroleum site
- Provision for the relevant activities and the environmental risks and environmental impacts they involve in a WWMP and a spill management plan, as part of the EMP.
- Monitoring, management and reporting in accordance with the WWMP and spill management plan. All stages of the framework should be developed in consideration of the waste management hierarchy.

While the Code of Practice for Petroleum Activities in the Northern Territory partly addresses recommendation 5.5 of the HF Inquiry (Pepper et al., 2018) by providing the objectives and minimum standards for a wastewater management framework, it does not present available options for managing water used in shale gas and oil operations, or which options may become available as the industry develops.

4.1.4 Waste management hierarchy

The waste hierarchy outlined in the National Waste Policy, 2018, must be implemented by interest holders when developing their WWMP. The hierarchy of resource used for wastewater generation is summarised as follows (Figure 4):

- Avoid: eliminate the generation of waste through design modification
- Reduce: reduce unnecessary resource use or substitute a less resource-intensive product or service
- Re-use: reuse a waste without further processing
- Recycle: recover resources from waste
- Treatment: treat the waste to reduce the hazard of the waste prior to disposal
- Disposal: disposal of waste if there is no viable alternative.

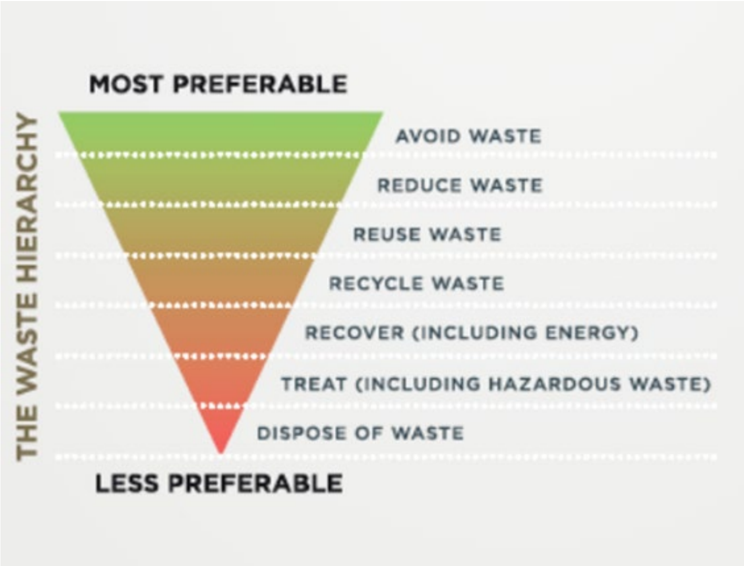


Figure 4. Principles of the waste hierarchy (Commonwealth of Australia, 2018)

4.1.5 Industry Environmental Management Plans (EMPs)

EMPs are prepared with reference to the NT Petroleum (Environment) Regulations, Code of Practice for Petroleum Activities in the Northern Territory and the Exploration Agreements between a proponent company, Native Title holders and the Northern Land Council (NLC). The overall objective of the EMP is to ensure that the activities, are carried out in a manner by which the environmental impacts and environmental risks will be reduced to a level that is as low as reasonably practicable and acceptable.

More specifically, an EMP aims to:

- address regulatory requirements
- provide site-specific impact management strategies to assist industry in maintaining a positive position in the local community throughout its program

- align with the principles of Ecological Sustainable Development (ESD) through the adoption of responsible development practices that are designed to maximise social benefit, whilst minimising the level of impact on the surrounding ecosystems
- provide a description of site-specific aspects of the existing environment (physical, biological, social and cultural)
- provide site-specific plans for review, monitoring and rehabilitation
- be a practical and usable document, with environmental management principles that are easily implemented and effective

4.2 Wastewater management practices in NT

Stakeholder engagement conducted with industry and government through workshops, one-on-one discussions and surveys provided baseline data on current practices, sources of wastewater within processes, treatment and reuse and beneficial use options. Stakeholders included regulators, industry proponents, related and proximal industries and key community advisory members. They were asked the following questions:

- What are likely water quantity and quality requirements for a range of shale gas and oil development scenarios?
- What are the water quality requirements for reuse or recycling of water in and from shale gas and oil activities?
- What treatment options are available and used?
- What are current wastewater qualities, process steps, treatment options, issues, disposal challenges, chemistry issues, and examples of successful beneficial reuse?
- What can we learn from onshore gas operations in other states and internationally?
- How are these industries dealing with wastewater?
- What are the current limitations and challenges?
- What other industries in the region are interested in an NT-based central treatment facility?

Engagement with stakeholders revealed that the exact quantities and qualities of flowback water and produced water likely to be generated for shale gas development are dependent on local geologies and extraction methods employed.

There is a need to understand the composition and time-evolution of flowback and produced waters in the Australian locations where hydraulic fracturing takes place.

Once wastewaters have been characterised, a framework can guide industry and regulators on optimal approaches for re-use, recycling, treatment and disposal based on a ‘fit for purpose’ approach. A Geological Bioregional Assessment within the Beetaloo basin, assessing flowback water produced from shale gas extraction by Santos and Origin Energy, has provided water quality data and improved understanding of wastewater management (Apte et al., 2021).

4.2.1 Wastewater treatment during exploration phase in NT

Wastewater treatment ponds and tanks are used onsite as the primary waste treatment method to reduce shale gas wastewater volumes prior to offsite disposal. Evaporation rates are maximised by ensuring there is sufficient cycling between open and enclosed tanks to maintain a small discrepancy between the salinity of water held in open storage and enclosed storage. Open tanks enhance evaporation from wastewater, limiting the need for offsite trucking. Based on the strong water deficit of the region, evaporation is the most suitable and safest method for this purpose. Mechanical enhanced evaporators can maximise evaporation rates and minimise associated storage and transport costs.

Wastewater recovered from the well during the flowback phase is stored in above-ground double-lined tanks. The tanks are most commonly located in a purpose-designed bunded containment tank pad area with real-time, continuous leak detection and water control structures. Tank levels are continuously monitored to ensure minimum freeboard is maintained. As a precautionary measure all wastewater must be stored in enclosed tanks in the event of significant rainfall.

According to the EMPs, the lease pad is surrounded by a bund of sufficient volume to contain and prevent potential release of contaminants in the event of a major spill. The drill cutting and drilling mud sump is lined with a composite, 5-layer impermeable barrier that meets the standards specified in the Code. The drill cuttings sump has a useable volume in excess of 2,400 m^3 and is operated with a minimum 1,300 mm freeboard to manage extreme rainfall events. Monitoring of wastewater levels within sumps and tanks is undertaken at least daily during drilling and well testing, with wastewater pond storage curves compiled and updated to track wastewater volumes onsite. Each wastewater tank is equipped with level sensors to monitor the fluid volumes in real time. Automated cut off sensors are also deployed to ensure wastewater tank levels do not exceed the safe operating level and 1:1000 average recurrence interval freeboard requirements. Where freeboard requirements are exceeded, well operations should cease in accordance with the response criteria outlined in the WWMP.

When the wastewater tanks are decommissioned, the associated residual solids, brines and liners are removed and disposed of at an appropriately-licensed waste disposal facility. Any remaining flowback fluid is transported by road to a licenced disposal facility. Off-site disposal is via licenced facility. No recycling or re-use of produced water or flowback fluid has been proposed in the EMPs.

Based on consultation with the industry and government, there are opportunities for centralisation or decentralisation of treatment approaches for optimisation of wastewater management. It is difficult to make any firm decisions in this regard during this early exploration phase of the shale gas industry. Complementary industries such as mining could be interested in a centralised NT treatment facility. Economic feasibility studies and market analysis would be needed to determine viability and options. Some of the challenges listed above and information gaps as highlighted during the stakeholder consultation, are addressed in later sections of this report.

4.3 Review of treatment technologies

Water treatment technologies are divided into six categories: physical, thermal, proprietary, chemical, biological and membrane-based.

4.3.1 Physical treatment technologies

Physical treatment technologies for produced water remove substances through forces, such as gravity, electrical attraction, and van der Waal forces, as well as by physical barriers (Jain et al., 2017). These technologies offer several advantages, such as their robustness, minimal energy requirements (usually 0.007-0.6 $kWhm^{-3}$) (Vlasopoulos et al., 2006), and the absence of chemicals or significant human resources (Fakhru'l-Razi et al., 2009). Nonetheless, physical treatment techniques are associated with some significant limitations, including extended retention times, substantial space requirements, and the production of secondary waste (Fakhru'l-Razi et al., 2009; Heins and Peterson, 2005; Igunnu and Chen, 2014).

Filtration

Filtration technology is extensively used for the removal of oil and grease, and total organic carbon from produced water (Colorado School of Mines, 2009). Filtration is a process that utilises various types of media, such as sand, gravel, anthracite, and walnut shells, for the treatment of produced water (Igunnu and Chen, 2014). The use of filtration is not influenced by water salinity and is applicable to all types of produced water. Media filtration technology is highly efficient, with a reported efficiency of more than 90% (Colorado School of Mines, 2009; Igunnu and Chen, 2014). Coagulants can be added to the feedwater prior to filtration to further enhance the process efficiency. However, the regeneration of filter media and the proper disposal of solid waste are significant drawbacks of this process.

The filter media's pore sizes and surface properties can vary, leading to fouling or clogging of the filter media, thereby reducing the filtration efficiency and necessitating more frequent replacement or cleaning (Igunnu and Chen, 2014). Additionally, certain filter media may require pre-treatment or backwashing to remove accumulated solids and prolong the media's lifespan.

Effective management of solid waste is a critical consideration for the filtration process. Depending on the type of filter media used, solid waste may consist of sand, gravel, and other particulate matter. Proper handling and disposal of this waste are essential to minimize environmental impacts and comply with local regulations. The solid waste can be managed on-site or transported to a waste management facility for proper disposal (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Flotation

Flotation technology is widely used for the treatment of conventional oilfield-produced water. The technology is a commonly used process that involves the separation of suspended particles using fine gas bubbles, which are more effective than sedimentation. The process entails injecting gas into produced water, causing suspended particulates and oil droplets to attach to the air bubbles as they rise. The resulting foam is removed as froth from the water surface (Casaday, 1993). Flotation has proven effective in removing various contaminants from produced water, including grease and oil, natural organic matter, volatile organics, and small particles, without the need for chemicals except for coagulants to enhance removal of target contaminants (Casaday, 1993; Colorado School of Mines, 2009; Igunnu and Chen, 2014).

There are two main types of flotation technology, namely dissolved gas flotation and induced gas flotation, which differ in the method of gas bubble generation and the resultant bubble sizes. In dissolved gas flotation units, gas is introduced into the flotation chamber either by vacuum or by creating a pressure drop. On the other hand, induced gas flotation units rely on mechanical shear or propellers to create bubbles (Çakmakce et al., 2008). Gas flotation can remove particles as small as 25 µm and can even remove contaminants down to 3 µm if coagulation is added as pre-treatment. However, gas flotation cannot remove soluble oil constituents from water (Colorado School of Mines, 2009; Igunnu and Chen, 2014). Flotation is most effective when gas bubble size is less than oil droplet size and it works best at low temperature since it involves dissolving gas into the water stream.

Hydrocyclones

Hydrocyclones exploit centrifugal force to segregate solids from liquids based on their densities (Igunnu and Chen, 2014). Typically, hydrocyclones are composed of a cylindrical inlet section and a conical outlet section, constructed from metals, plastics, or ceramics, and they operate without any moving components. The effectiveness of the hydrocyclone relies heavily on the angle of the conical section (Colorado School of Mines, 2009; Igunnu and Chen, 2014). Hydrocyclones have been extensively employed for the treatment of produced water, with a capacity to eliminate particles in the range of 5-15 µm (Colorado School of Mines, 2009; Igunnu and Chen, 2014). The annual amount of produced water processed via hydrocyclones exceeds 8 million barrels per day (Igunnu and Chen, 2014; Svarovsky, 1992). They are frequently used in conjunction with other techniques as a pre-treatment step. Hydrocyclones are long-lasting, require no pre-treatment of feed water, and do not necessitate the use of chemicals. Nonetheless, a significant drawback of hydrocyclones is the creation of a concentrated slurry of solid waste.

4.3.2 Thermal treatment technologies

Thermal treatment technologies are widely utilised in water treatment processes to separate or degrade water contaminants through the application of heat. Such technologies are usually preferred in regions with low energy costs. Prior to the introduction of membrane technology, thermal separation processes were the conventional technology employed for water desalination. Though membrane technologies have become more prevalent, recent advancements in thermal process engineering have made thermal treatment more viable and competitive, especially in the treatment of highly polluted water (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

There are various thermal technologies available for treating produced water, including distillation, evaporation, and crystallisation (Igunnu and Chen, 2014). Distillation involves heating produced water to produce steam, which is then condensed to produce purified water, leaving behind any contaminants. This process effectively removes a broad spectrum of contaminants from produced water, such as dissolved salts, hydrocarbons, and heavy metals. Evaporation is another thermal treatment technology that involves heating produced water to create steam. The steam is subsequently condensed, leaving behind purified water and any solids or contaminants in the produced water. This process is especially useful in eliminating dissolved solids and salts from water. Crystallisation is a thermal separation technology that involves cooling the produced water to form crystals of salts and other minerals, which can then be removed from the water, leaving behind purified water. This technique is especially effective in eliminating dissolved salts from produced water.

Multistage flash

Multistage flash (MSF) distillation has been established as a reliable and well-established technology for desalination of brackish and seawater (Igunnu and Chen, 2014). The operational principle of MSF distillation is based on pressure reduction for water evaporation instead of temperature elevation. Specifically, the feedwater undergoes pre-heating and enters a chamber with lower pressure, where it instantly undergoes steam flash evaporation (Igunnu and Chen, 2014; U.S. Bureau of Reclamation, 2003). MSF treatment can recover up to 20% of water, but often necessitates post-treatment due to its typical total dissolved solids (TDS) concentration of 2-10 mg/L in the recovered water (Colorado School of Mines, 2009; Igunnu and Chen, 2014). A key challenge in MSF operation is the formation of scale on heat transfer surfaces, which necessitates the use of scale inhibitors and acids. The costs of MSF treatment can vary depending on factors such as size, location, and construction materials (Ettouney et al., 2002). In terms of energy consumption, MSF treatment requires between 3.35 and 4.70 kWh/bbl (Darwish et al., 2003).

Multi-effect distillation

Multi-effect distillation (MED) is a desalination technology that involves the conversion of saline water into steam, which is then condensed and recovered as pure water (Igunnu and Chen, 2014). Multiple effects are utilised in MED to enhance its efficiency and minimise energy consumption. MED’s significant advantage is its energy efficiency obtained through the integration of several evaporator systems. The recovery rate of product water varies between 20% to 67% based on the type of evaporator design utilised (U.S. Bureau of Reclamation, 2003). However, scaling issues associated with old designs have limited its widespread use for water production. To address this challenge, falling film evaporators have been introduced to enhance heat transfer rates and reduce the rate of scale formation (Hamed, 2004). MED has a life cycle of 20 years and can be used to treat a wide range of feed water quality, similar to MSF. It is a suitable option for treating high TDS produced water (Colorado School of Mines, 2009; Hamed, 2004; Igunnu and Chen, 2014). To prevent scaling, scale inhibitors and acids may be required, and pH control is essential to prevent corrosion.

Vapour compression distillation

Vapour compression distillation (VCD) is a well-established desalination technology for treating seawater and reverse osmosis (RO) concentrate (Colorado School of Mines, 2009; Igunnu and Chen, 2014). The VCD process involves compressing the vapour generated in the evaporation chamber using thermal or mechanical means, resulting in a temperature and pressure increase. The heat of condensation is then returned to the evaporator as a heat source. VCD is known for its reliability and efficiency in desalination and can operate at temperatures below 70 °C, reducing scale formation problems (Igunnu and Chen, 2014; Khawaji et al., 2008).

Compared to multi-effect distillation and multistage flash, the energy consumption of a VCD plant is significantly lower. The operating cost of VCD depends on several factors such as plant size, construction materials, location, zero liquid discharge target, and purpose. Cogeneration of low-pressure steam can help reduce the overall cost of VCD. While VCD is commonly used for seawater desalination, various enhanced vapour compression technologies have been successfully applied to treat produced water (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Multi-effect distillation–vapour compression hybrid

The application of a hybrid process of multi-effect distillation and vapour compression has, recently, been proposed as an efficient technology for produced water treatment. The hybrid process has been shown to provide increased production and enhanced energy efficiency compared to conventional MSF plants. This technology is expected to replace older MSF plants due to its superior performance (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

GE has developed produced water evaporators that employ mechanical vapour compression. These evaporators offer several advantages over conventional produced water treatment methods, including reduced chemical use, lower costs, less severe fouling, easier handling, softer sludge, and other waste streams (Heins and Peterson, 2005). The produced water evaporators have a long service life of up to 30 years (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Evaporation

Evaporation techniques involve the application of thermal energy to a liquid stream in order to vaporise a portion of the water, resulting in the production of freshwater and brine with a higher concentration of total dissolved solids (TDS). In light of increasingly strict regulations in the United States regarding the treatment of wastewater with high volumes and salinity, evaporation and crystallisation techniques have been repeatedly cited as the sole viable technological solution (Blauch et al., 2009).

Evaporation with mechanical vapour compression

Various designs and operational strategies are available among the evaporation technologies, which are suitable for treating produced waters with high dissolved salts concentration. Vertical tube, falling film, and mechanical vapour recompression (MVC) are the most promising approaches for optimising heat transfer (Estrada and Bhamidimarri, 2016; Fakhru’l-Razi et al., 2009). In MVC, a tube evaporator provides superheated, compressed vapor heat to the brine. This process includes pre-heating of wastewater using hot condensates and brine streams. The primary energy requirement for this system is electricity utilised for vapour compression. The MVC process is highly efficient and reliable and can be operated at lower temperatures (less than 7 °C). This characteristic offers significant opportunities for treating fracturing wastewater (65–100 °C) with low energy demand (Akzo Nobel nv, 2004; Igunnu and Chen, 2014; Shaffer et al., 2013). Moreover, the arrangement of tubular heat exchangers in a vertical orientation enhances the heat transfer rate and optimizes the evaporation process. The tubular heat exchangers use a film-like feed stream flowing over the internal surface of the tubes, while the superheated vapourised condensates flow along the outside surface (Heins and Peterson, 2005).

Evaporation ponds

Evaporation ponds are man-made, open-air basins that employ solar radiation to vapourise produced water, making them a preferred technology in arid and warm climates with high rates of evaporation, flat terrain, and low-cost land (Igunnu and Chen, 2014). These ponds have been utilised both on-site and off-site for treating produced water, and they are considered a cost-effective solution. Once a significant proportion of the initial water volume has evaporated, the remaining concentrated salt sludge is either retained in the ponds or transported to off-site locations for disposal. Depending on the quality of the produced water and other regulatory standards, the ponds may require lining or construction on natural geological confining layers to prevent water infiltration into the aquifer (ALL Consulting, 2003; Igunnu and Chen, 2014). The design of such ponds is based on whether the produced water is to be prevented from infiltrating the subsurface or whether it should be prevented from migrating downwards (ALL Consulting, 2003). To optimise the evaporation process, ponds are characterised by high surface area to volume ratios. To avoid waterfowl and other species from coming into contact with contaminants present in produced water, the ponds must be covered with nets or other barriers (Colorado School of Mines, 2009; Igunnu and Chen, 2014). The major drawback of evaporation ponds is the large area required (Ahmed et al., 2001; Velmurugan and Srithar, 2008). Another disadvantage is that they lead to loss of water to the environment when water recovery is the objective of the water treatment process.

4.3.3 Proprietary treatment technologies

Freeze-thaw evaporation

The Freeze-thaw evaporation (FTE®) technology originally developed in 1992 by the Energy & Environmental Research Centre (EERC) and B.C. Technologies Ltd (BCT), is a well-established and robust method for treating and disposing of produced water (Igunnu and Chen, 2014). FTE® works by utilising a combination of freezing, thawing, and evaporation. The freezing point of produced water is lowered below 0°C due to the presence of salts and other dissolved constituents. As a result, cooling produced water below 0°C, but not below its freezing point, leads to the formation of relatively pure ice crystals and an unfrozen solution with a high concentration of dissolved constituents. The ice is collected and melted to obtain clean water, while the unfrozen solution is drained from the ice. During winter, about 50% of the water can be recovered from this process, but in other seasons, FTE® operates like a conventional evaporation pond without any water recovery. FTE® is capable of removing more than 90% of heavy metals, total dissolved solids (TDS), volatile and semi-volatile organic compounds, total suspended solids, and total recoverable petroleum hydrocarbons present in produced water (Boysen, 2007; Boysen et al., 1999; Igunnu and Chen, 2014). FTE® is a chemical-free, low-maintenance technology that has a lifespan of approximately 20 years and requires no supporting infrastructure or supplies, thereby making it easily operable and monitorable (Colorado School of Mines, 2009; Igunnu and Chen, 2014). However, FTE® can only be implemented in regions where temperatures frequently fall below freezing and typically necessitates a significant amount of land. Waste disposal is a critical aspect of this technology since it generates considerable concentrated brine and oil.

Dewvaporation: AltelaRain^{SM} process

The dewvaporation process is a desalination technology that has been used in the development of the AltelaRain^{SM} system for the commercial treatment of produced water (Godshall, 2006; Igunnu and Chen, 2014). This system utilises counter current heat exchange to produce distilled water, with heat being applied to the produced water to generate water vapour that is subsequently condensed to produce purified water. The system has been reported to have a high removal rate of heavy metals, organics, and radionuclides from produced water, as well as the ability to process approximately 100 bbl/day of water with salt concentrations over 60,000 mg/L TDS (Igunnu and Chen, 2014).

The AltelaRain^{SM} system operates at ambient pressures and low temperatures, resulting in low energy requirements, which makes it a suitable water treatment option for remote oil wells without access to a high-power grid (Godshall, 2006; Igunnu and Chen, 2014). However, there is no available information on the cost of the system, which may be a potential drawback. The successful application of dewvaporation technology in the AltelaRain^{SM} system represents a significant advancement in the field of desalination and has promising implications for the treatment of produced water.

4.3.4 Chemical treatment technologies

Chemical methodologies are employed to treat the constituents of produced water (Jain et al., 2017). Nonetheless, the implementation of certain chemical treatments can be energy-intensive, necessitating over 1.5 $kWhm^{-3}$. Furthermore, a majority of these techniques result in significant amounts of secondary chemical waste, which presents an obstacle in terms of disposal (Vlasopoulos et al., 2006). There are also substantial operational and chemical expenses associated with these treatments, as well as a considerable amount of sludge production (Fakhru'l-Razi et al., 2009; Igunnu and Chen, 2014).

Adsorption

Adsorption is typically employed as a final polishing step in the treatment process, rather than as a standalone technology, due to the risk of organic overloading of adsorbents (Hu and Xu, 2020). Nevertheless, adsorption has been successfully used to remove numerous contaminants from water, including manganese, iron, total organic carbon (TOC), benzene, toluene, ethylbenzene, xylene (BTEX), oil, and heavy metals (Colorado School of Mines, 2009; Igunnu and Chen, 2014). However, adsorption is unable to completely remove all pollutants, and is instead utilised as a robust partial treatment due to the high cation-exchange capacity of adsorbents for inorganic pollutants, and the high surface area for organic pollutants.

There are a variety of adsorbents available, including activated carbon, organoclays, activated alumina, and zeolites (Spellman, 2003). The adsorption process is applicable to water treatment irrespective of salinity and requires a vessel to contain the media, as well as pumps for periodic backwashing to remove particulates trapped within the media voids. Replacement or regeneration of the media may be necessary depending on feed water quality and media type, with media usage rate being one of the main operational costs of adsorption technology (Colorado School of Mines, 2009; Igunnu and Chen, 2014; Spellman, 2003). Regeneration of media is accomplished using chemicals when active sites become blocked, which may generate liquid waste. Replacement of media requires proper solid waste management.

Granular activated carbon is preferable to powdered activated carbon for the oil and gas industry due to the lower carbon usage rate and associated operational costs (Butkovskyi et al., 2017; Hackney and Wiesner, 1996). Adsorption onto activated carbon is highly effective for a wide variety of organic compounds, but is highly dependent on various factors, such as the dose and contact time, intrinsic properties of activated carbon, size, chemical structure, and polarity of the adsorbates, as well as solution properties like the presence of competing organic matter, pH, and salinity (Butkovskyi et al., 2017).

Chemical oxidation

Chemical oxidation is an established and reliable technology that has been widely used for the removal of various contaminants from produced water, such as colour, odour, chemical oxygen demand, biochemical oxygen demand, organics, and some inorganic compounds (Barratt et al., 1997; Igunnu and Chen, 2014). The mechanism of chemical oxidation is based on the oxidation-reduction (redox) reactions that occur in produced water, where free electrons cannot exist in solution (ALL Consulting, 2003). Commonly used oxidants include ozone, peroxide, permanganate, oxygen, and chlorine, which are mixed with contaminants to break them down. The rate of oxidation is affected by several factors, such as the chemical dose, type of oxidant, raw water quality, and contact time between oxidants and water (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Despite its effectiveness, chemical oxidation may be associated with high chemical costs (American Society of Civil Engineers & American Water Works Association, 1998) and energy consumption, which accounts for around 18% of the total cost of operations and maintenance (Colorado School of Mines, 2009; Igunnu and Chen, 2014). However, chemical oxidation requires minimal equipment and has a long service life of 10 years or more. Additionally, solid separation post-treatment may be employed to remove oxidized particles (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Advanced oxidation

Advanced oxidation processes (AOPs) are a promising technology that relies on the production of highly reactive hydroxy radicals (OH) to degrade and mineralise organic bio-refractory pollutants in water (Silva et al., 2017). These processes can also be employed for water disinfection. Examples of AOPs include the Fenton process, ozonation, ultraviolet (UV) radiation with or without hydrogen peroxide, heterogeneous photocatalysis, electrochemical oxidation, and catalytic wet air oxidation.

AOPs have shown potential for the treatment of wastewater generated from hydraulic fracturing (HF) operations to remove organic and inorganic contaminants (e.g. ammonium, cyanide, thiosulfuric, and sulfion), disinfect the water, and eliminate odour and colour (Igunnu and Chen, 2014). Frequently used oxidants in AOPs for HF wastewater treatment are ozone, hydrogen peroxide, chlorine, and Fenton’s reagent (hydrogen peroxide and ferrous iron). Hydrodynamic cavitation, ozonation, acoustic cavitation, and electrochemical oxidation can also be integrated into the process to remove organic matter, bacteria, and scalants. The goal of these treatments is to enable the reuse of fracturing wastewater or to pre-treat the water before RO treatment, allowing it to be safely discharged to the surface (Igunnu and Chen, 2014).

4.3.5 Biological treatment technologies

The ubiquity of bacteria in the environment necessitates their presence in produced water, as unconventional oil and gas development activities are conducted in non-sterile conditions (Liden et al., 2018). The bacteria in a waste stream may arise from the geological formation at shallow depths or introduced to water handling infrastructure, fracturing fluid amendments, or source water used to create the fracturing fluid (Mohan et al., 2013). For shale gas flowback and produced water with moderate salinity (TDS = 22.5 g/L) and high acetic acid content (16 mg/L), aerobic biological treatment in a sequencing batch reactor is appropriate (Butkovskyi et al., 2017; Lester et al., 2015). The removal of VOCs, polycyclic aromatic hydrocarbons, and phthalates during aerobic and anaerobic treatment of industrial wastewaters has been reported to be low to moderate (Butkovskyi et al., 2017; Foght, 2008; Mrowiec et al., 2013; Steliga et al., 2015; Suschka et al., 1996). Polar organic compounds can be effectively removed by membrane bioreactors through a combination of sorption and biodegradation, but the removal of hydrophilic compounds is variable and dependent on their structure (Butkovskyi et al., 2017; Tadkaew et al., 2011).

Biological aerated filters

Biological aerated filters (BAFs) are a type of permeable media filter that rely on aerobic conditions to facilitate the biochemical oxidation and removal of organic pollutants from contaminated water (Igunnu and Chen, 2014). The media used in BAFs is typically no larger than 4 mm in diameter to prevent clogging of pore spaces when sloughing occurs (USEPA, 1980). BAFs have been shown to effectively remove a wide range of pollutants from produced water, including oil, ammonia, suspended solids, nitrogen, chemical oxygen demand (COD), biochemical oxygen demand (BOD), heavy metals, iron, soluble organics, trace organics, and hydrogen sulfide (Colorado School of Mines, 2009; Igunnu and Chen, 2014; Su et al., 2007). However, BAFs are most effective when treating produced water with chloride levels below 6,600 mg/L (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

BAFs require upstream and downstream sedimentation processes to allow for the use of the full bed of the filter. Removal efficiencies of up to 70% for nitrogen, 80% for oil, 60% for COD, 95% for BOD, and 85% for suspended solids have been achieved with BAF treatment (Igunnu and Chen, 2014; Su et al., 2007). Furthermore, nearly 100% of the water used in the BAF process is recovered since waste generated is removed in the solid form (Ball, 1994; Igunnu and Chen, 2014).

BAFs typically have a long lifespan and do not require any chemicals or cleaning during normal operations. The power requirement for BAFs ranges from 1–4 kWh/day, and capital represents the largest cost of this technology. Solid disposal is required for accumulated sludge in sedimentation basins and can account for up to 40% of the total cost of this technology (Igunnu and Chen, 2014; Su et al., 2007).

4.3.6 Membrane-based treatment technologies

The separation of constituents using membranes is predominantly achieved through exclusion mechanisms based on size, but not exclusively, by utilising selective barrier layers (Munirasu et al., 2016). Both pressure-driven and thermally-driven membrane-based technologies have been developed and utilised for the treatment of wastewater from shale oil and gas (Tong et al., 2019). These technologies demonstrate significant potential in the treatment of saline wastewater owing to their high-quality permeate, flexibility, and desalination abilities (Ahmad et al., 2021). Despite the capacity to effectively eliminate various inorganic and organic pollutants, membrane separation technologies are restricted by their insufficient salinity threshold and technical immaturity. Additionally, effective pre-treatment measures are required to improve membrane performance and water product quality through integration with membrane technologies. Figure 5 shows membrane technologies proposed for shale gas treatment.

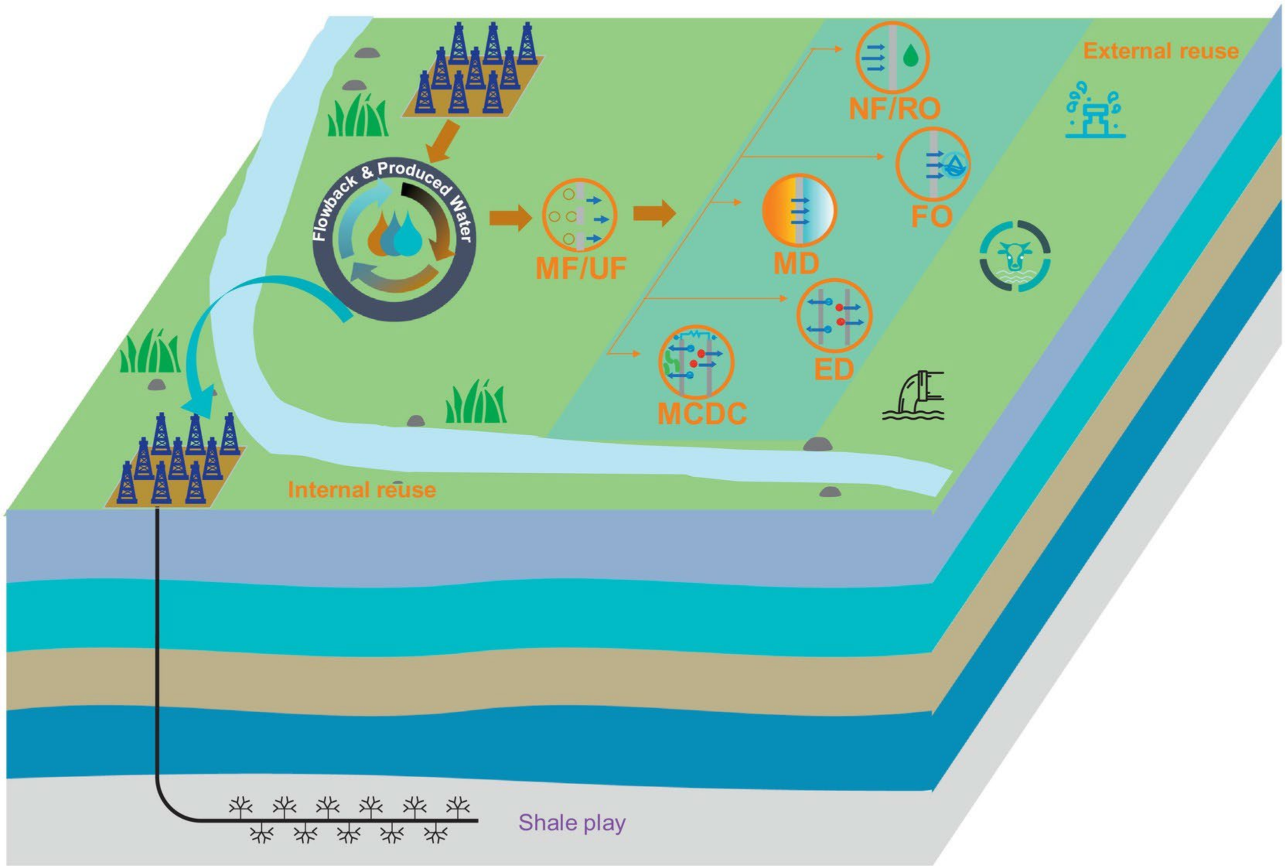


Figure 5. Current membrane-based technologies for reuse in shale gas (Chang et al., 2019). ED: Electrodialysis; FO: Forward osmosis; MD: Membrane distillation; MCDC: Microbial capacitive desalination cell; MF: Microfiltration; UF: Ultrafiltration; NF: Nanofiltration; RO: Reverse osmosis.

Membrane distillation

Membrane distillation has emerged as a promising technique for desalinating high salinity waters (Estrada and Bhamidimarri, 2016; Sun et al., 2019). This separation process is based on thermal differences, wherein the influent stream is heated, and only vapour molecules are permitted to pass through a porous hydrophobic membrane to the cooler side as permeates. The difference in vapour pressure between the two membrane sides accelerates the process, and it can be operated at more ambient temperatures than conventional thermal methods (Estrada and Bhamidimarri, 2016). The hydrophobic microporous membrane, which is non-wetted, separates the hot feed stream and the cold permeate or distillate stream (Kalla, 2021). Saline wastewater need not be heated to its boiling point since a temperature difference of 10-20 °C between the membrane surfaces is sufficient for high performance (Alkhudhiri et al., 2012; Minier-Matar et al., 2014).

However, the desalination of produced waters via membrane distillation is limited due to high concentrations of hydrocarbons that cause membrane wetting and performance impairment. A pre-treatment using Fenton oxidation to degrade the organics can increase the effectiveness of the subsequent membrane distillation process and improve the final product's quality (Ricceri et al., 2019).

Forward osmosis

Forward osmosis (FO) is a membrane-based separation process that relies on the osmotic pressure gradient to eliminate TDS from a solution (Estrada and Bhamidimarri, 2016; Sun et al., 2019). The feed solution is transported through a semi-permeable membrane, propelled by the disparity between the osmotic pressure of the treated wastewater and a concentrated draw solution (i.e. the draw solution; Figure 6) (Estrada and Bhamidimarri, 2016).

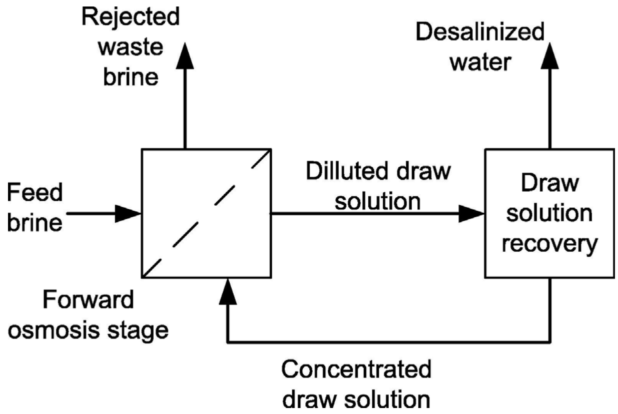


Figure 6. Forward osmosis process showing draw solution re-concentration (Estrada and Bhamidimarri, 2016).

In the treatment of hydraulic fracturing wastewater, it is essential to ensure that the concentration of specific components in the draw solution surpasses that of the wastewater (Shaffer et al., 2013). The FO technique involves two stages, where the influent is initially passed through a membrane, causing dilution of the draw solution, followed by the separation of water from the draw solution via RO or thermal distillation to produce high-quality effluent and re-concentrate the draw solution (Coday and Cath, 2014).

Despite the numerous advantages of FO, such as its operation at low pressure, which reduces the likelihood of fouling and extends the membrane's lifetime, its application in the treatment of hydraulic fracturing wastewater remains limited, mainly due to the need to improve membrane properties (Shaffer et al., 2013). The efficiency of the FO process relies on the appropriate selection of the draw solution, which should be inexpensive, highly soluble to avoid scaling issues during recovery, and provide the necessary osmotic pressure to induce sufficient flux across the membrane.

Reverse osmosis

Reverse osmosis (RO) is a technique for separating substances through a pressure-driven membrane process. Hydraulic pressure is applied to suppress the osmotic pressure of the feed solution, thereby compelling permeate (i.e. clean water) to pass through a dense, non-porous membrane (Igunnu and Chen, 2014; Spiegler and Kedem, 1966). While seawater RO is capable of removing contaminants as small as 0.0001 µm, it is challenged by the issue of membrane fouling and scaling (Colorado School of Mines, 2009; Igunnu and Chen, 2014; Mark, 2007). Although RO is a well-established desalination method for seawater on a large scale, it may not be suitable for high-salinity shale gas wastewaters. RO could be employed to treat wastewaters with low total dissolved solids (TDS) for reuse (Igunnu and Chen, 2014). Currently, RO is restricted to treating streams with TDS below 50,000 ppm (Schantz et al., 2018). Figure 7 compares thermal methods, forward osmosis and reverse osmosis.

Ion exchange technology

Ion exchange is a widely applied technology, including for the treatment of coal bed methane produced water. It is especially useful in the removal of monovalent and divalent ions and metals by resins from produced water (Clifford, 1999; Igunnu and Chen, 2014). Nadav (1999) suggested that ion exchange has the potential to remove boron from RO permeate of produced water. Ion exchange technology has a lifespan of around 8 years and requires pre-treatment options for solid removal. It also requires the use of chemicals for resin regeneration and disinfection. The operating cost accounts for more than 70% of the overall cost of this technology (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

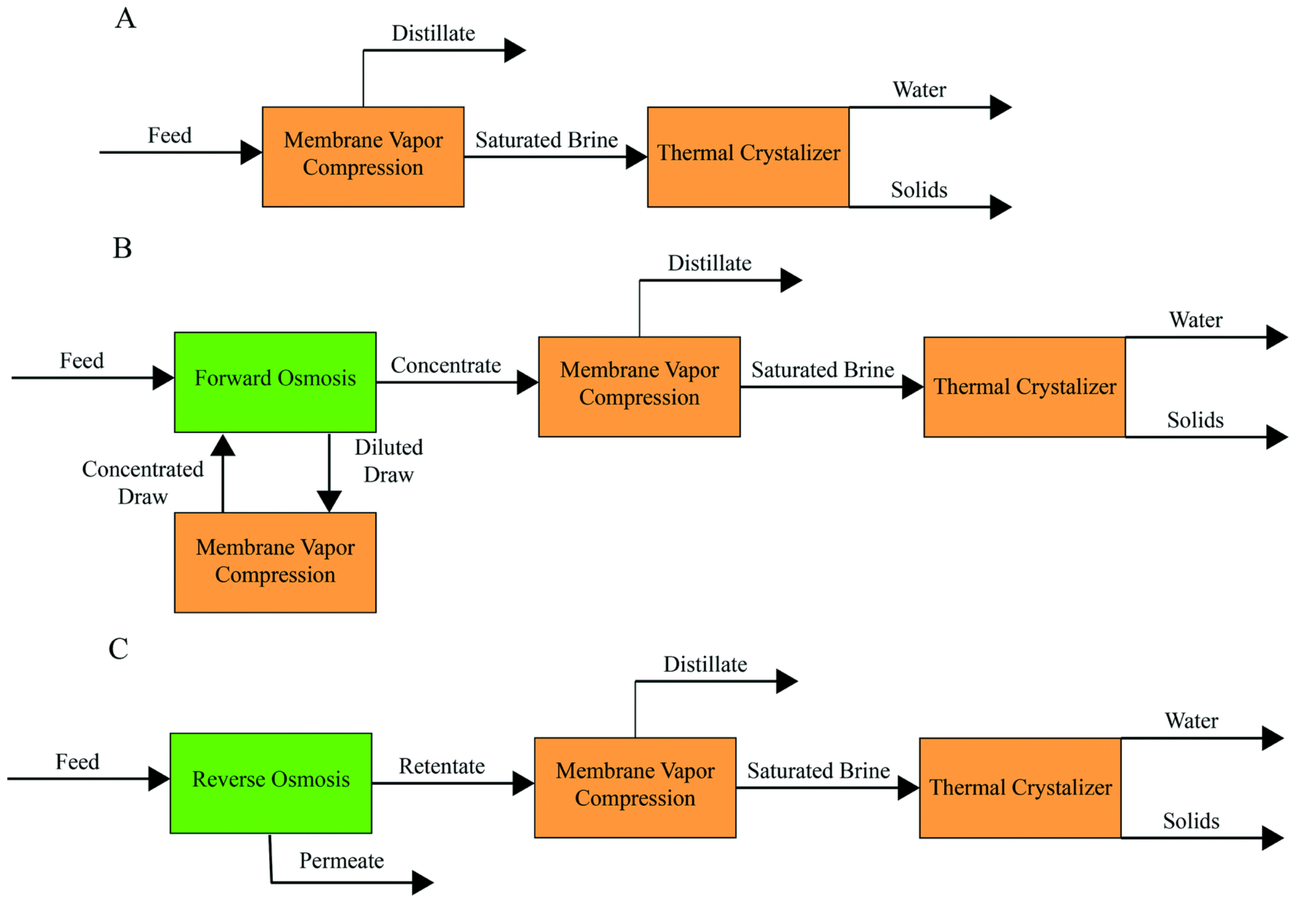


Figure 7. Process-flow diagram for (A) thermal methods, (B) Forward osmosis (FO), and (C) Reverse osmosis (RO). In cases B and C, a thermal process is still required to remove the remaining water from the feed following the membrane process. Thermal processes (less efficient) are in orange, while membrane processes (more efficient) are in green (Schantz et al., 2018).

Electrodialysis and electrodialysis reversal

Electrodialysis (ED) and ED reversal (EDR) are established electrochemically-driven desalination techniques that employ ion exchange membranes to separate dissolved ions from water (Igunnu and Chen, 2014). The process is executed through a sequence of ion-exchange membranes that comprise of electrically charged functional sites, arranged in an alternating manner between the anode and cathode, to eliminate charged substances from the feed water. An anion-selective membrane solely permits anions to pass through it, whereas a cation-selective membrane allows only cations to pass through it. EDR utilises periodic reversal of polarity to optimise its performance (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

The application of EDR and ED technologies has been limited to laboratory scale for produced water treatment. Although ED is a proficient produced water treatment technology, it is most effective for treating relatively low saline produced water (Sirivedhin et al., 2004). The lifetime of ED/EDR membranes is typically 4-5 years, but the technology has major limitations such as regular membrane fouling and high treatment cost (Colorado School of Mines, 2009; Igunnu and Chen, 2014). Despite its potential for highly saline water desalination in terms of energy and cost, ED fouling under complex wastewater feed is still an area that requires further investigation (Ahmad et al., 2021).

ED technology has been found to reduce the TDS level in flowback water (initial TDS approx. 60,000 mg/L) by approximately 27% (Peraki et al., 2016). The energy consumption of ED technology is comparable to that of vapour compression desalination system for treating flowback and produced water containing 40,000-90,000 ppm TDS (McGovern et al., 2014).

Microfiltration/Ultrafiltration

Microfiltration (MF) is a well-established membrane technology widely used for the separation of suspended particles (Nasiri and Jafari, 2017) and turbidity reduction. MF membranes have a relatively large pore size ranging from 0.1 to 3 µm and can operate in either cross-flow or dead-end filtration modes. MF has been demonstrated to effectively remove flocculated particulate matter and microorganisms (Jebur et al., 2021).

Ultrafiltration (UF) is another membrane technology that employs membranes with pore sizes between 0.01 and 0.1 µm. UF is primarily used for the removal of colour, odour, viruses, and colloidal organic matter (Colorado School of Mines, 2009; Igunnu and Chen, 2014). UF has been shown to be more effective than traditional separation methods in removing oil from produced water (He and Jiang, 2008), and it is more efficient than MF in removing hydrocarbons, suspended solids, and dissolved constituents from oilfield produced water (Bilstad and Espedal, 1996; Igunnu and Chen, 2014).

Both MF and UF operate at low transmembrane pressures (1–30 psi) and can serve as a pre-treatment to desalination. However, they cannot remove salt from water (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Polymeric/ceramic membranes

Polymeric and ceramic membranes are commonly used for the UF and MF treatment of water, respectively. Polymeric MF/UF membranes are manufactured from polymers such as polyacrylonitrile and polyvinylidene, while ceramic membranes are made from nitrides, carbides, and oxides of metals such as clays (Igunnu and Chen, 2014; Khemakhem et al., 2009). Full-scale facilities have employed ceramic UF/MF membranes for the treatment of produced water, resulting in product water that is substantially free of suspended solids and non-dissolved organic carbon (Faibish and Cohen, 2001a; 2001b; Gutiérrez et al., 2008; Igunnu and Chen, 2014; Konieczny et al., 2006; Lobo et al., 2006). Ceramic UF/MF membranes have demonstrated a lifespan of more than a decade, and they can function in both cross-flow filtration and dead-end filtration modes. Chemicals are not usually necessary for this process, with the exception of periodic cleaning of membranes and pre-coagulation to improve contaminant removal (Colorado School of Mines, 2009; Igunnu and Chen, 2014).

Moreover, other polymeric membranes such as poly-vinyl sulfonate (PVS), poly(4-styrenesulfonate) (PSS), polyacrylic acid (PAA), and poly(4-styrenesulfonic acid-co-maleic acid) (PSSM) have been tested for the removal of divalent cations that form scale (precipitates) from produced water. While PSSM and PSS were effective for Ba and Sr removal from lower salinity brines (TDS of 31,000 mg/L), their efficacy for Sr removal was limited in the absence of Ba in high salinity brines (TDS of 92,000 mg/L) (Shafer-Peltier et al., 2020).

Macro-porous polymer extraction technology

Macro-porous polymer extraction (MPPE) has been established as a highly effective technology and environmentally sustainable practice for the management of produced water in offshore oil and gas platforms (Akzo Nobel nv, 2004; Igunnu and Chen, 2014). MPPE is based on the principle of liquid-liquid extraction, where a specific extraction liquid is immobilised within macro-porous polymer particles having a diameter of approximately 1000 µm, pore sizes ranging from 0.1-10 µm, and porosity of 60-70%. In this process, produced water is passed through a column packed with MPPE particles containing the immobilized extraction liquid, which selectively removes hydrocarbons from the produced water. Continuous operation with simultaneous extraction and regeneration is possible by employing two columns (Akzo Nobel nv, 2004; Igunnu and Chen, 2014). The recovered hydrocarbons can be recycled or disposed of appropriately, and the stripped hydrocarbons can be condensed and separated from the feed water via gravity, while the product water is either reused or discharged. The primary drawback of the technology is its relatively high unit cost.

Qualitative comparison of membrane technologies

It is critical to choose appropriate treatment from the selection of various advanced membrane technologies to meet the treatment requirements. Table 1 presents a qualitative comparison of membrane technologies on their advantages and limitations, which determine the feasibility of implementing membrane-based technologies in the shale oil and gas industry. In the current state, more research is required for membrane technologies to compete with MVC as cost- and energy-effective wastewater treatment options (Tong et al., 2019).

Table 1. Qualitative comparison of membrane technologies used as main step for shale oil and gas wastewater treatment. A higher number of stars is indicative of more favourable features (Tong et al., 2019).

Feature	MVC	MF/UF	NF/RO	FO	MD
Technical Maturity	★★★	★★★	★★★	★★☆	★☆☆
Energy Efficiency	★★☆	★★★	★★★	★☆☆	★☆☆
Product Quality	★★★	★☆☆	★★★	★★★	★★★
Salinity Limit	★★★	★★★	★☆☆	★★★	★★★
Utilise Low-grade Thermal Energy	★☆☆	★☆☆	★☆☆	★★★	★★★
Capital Cost	★☆☆	★★★	★★★	★★☆	★★★
On-site Treatment	★★★	★★★	★★★	★★★	★★★

FO: Forward Osmosis; MD: Membrane distillation; MF: Microfiltration; MVC: Mechanical Vapour Compression; NF: Nanofiltration; RO: Reverse Osmosis; UF: Ultrafiltration

Beneficial reuse

Internationally, a range of membrane technologies are in use to improve wastewater qualities for reuse. However, examples of successful beneficial reuse applications are limited (irrigation and cooling towers, dust suppression). Segregation of waste streams to optimise reuse/recycling are more commonly in practice. Membrane fouling, lack of full-scale experience and high energy consumption are primary challenges with membrane technologies.

4.4 Discussion

Shale gas development in the NT is at the exploration stage. Onsite wastewater treatment ponds and tanks are the primary method used to reduce wastewater volumes prior to offsite disposal. Internationally, a range of membrane technologies is in use to improve wastewater qualities for reuse for future stages of development. Membrane fouling, lack of full-scale experience and high energy consumption are primary challenges with these technologies. No single technology is likely to result in the effluent requirements for discharge or re-use (outside direct hydraulic fracturing reuse). Membrane technologies in use for shale gas internationally include forward osmosis and ultrafiltration/membrane filtration, followed by membrane distillation, and electrically driven nanofiltration/reverse osmosis. Biologically active membranes are rarely used. More likely, a combination of pre-treatment techniques, existing use of evaporation ponds for volume reduction of highly saline wastewaters and new desalination available will have to be optimised in order to minimise the environmental impact of wastewaters from shale gas production by hydraulic fracturing.

Wastewater management practices are often largely driven by the economics and logistics of disposal options. With shale gas expected to maintain a significant role in energy systems for decades to come, new strategies will be crucial to minimise environmental and social impacts. While water reuse is an ongoing challenge for the shale gas industry, it is being actively explored and is likely to be important in the Australian shale gas sector.

5 Wastewater management KPIs

This section outlines the steps taken to develop key performance indicators (KPIs) for wastewater management options and presents the KPIs as currently defined.

We obtained stakeholder feedback on draft criteria, and linked KPIs with codes of practice for use in future optimisation assessment employing our MCDA approach.

5.1 Why KPIs?

KPIs provide a systematic approach to understanding the processes that generate particular waste and the possible management options. This approach helps to gain industry and regulator trust, and gives industry an adaptive and accessible approach to managing wastewater. KPIs provide relevant, reliable, and comparable information on gas operations based on a robust assessment of companies' environmental, social, and governance policies, practices and performance (Liroff, 2013). In addition, KPIs:

- drive operational efficiencies (reduced costs yield increased margins and profitability)
- are comparable and quantitative where possible, supporting efforts to improve performance
- provide a communication tool for stakeholders, so foster transparency and trust
- can inform environment protection and sustainable development
- protect and enhance companies' social license to operate and support continuous improvement.

The KPIs proposed for water management are classified into four categories: environmental, operational, social and economic indicators. The KPIs have been developed in consultation with key stakeholders and align with the NT Codes of Practice (Government of Northern Territory, 2019).

5.2 Proposed wastewater KPIs

Table 2 outlines the proposed wastewater KPIs, refined and parameterised during the project and used to develop the MCDA.

Table 2. Proposed wastewater KPIs

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
1. Environmental performance	Water use	Exploration phase Per fractured well Production phase Total freshwater used each year for completions (hydraulic fracturing) per unit of natural gas production including the freshwater used (in ML?) and natural gas production (i.e. total volume of natural gas produced)	Estimate the quantities and quality of water and wastewater from the petroleum activity. B.4.10.2 c	Minimise water use and manage stress on water resources.
	Water quality	Surface water and ground water quality pre- and post-drilling	Estimate the quantities and quality of water and wastewater from the petroleum activity List as per CoP Table 6: Minimum suite of analytes for groundwater monitoring.	Baseline monitoring essential. Prevent migration of methane and salts to groundwater as a result of the fractures.
	Soil quality	At operational region pre- and post-activity	Minimises impacts to soil resources	Baseline monitoring essential. Prevent contamination of land.
	Chemical use	Quantitative data each year/operation-region Specific chemical use – toxicity score can be used as metrics Supply CAS numbers of all chemicals used for individual wells	The name, type and quantity of each chemical used on each well throughout the well construction process must be recorded.	Transparency on chemical use
	Wastewater volume	Before evaporation and after evaporation	Estimate the quantities and quality of wastewater that will be removed from the petroleum site.	Volume reduction by evaporation
	Wastewater quality	List as per CoP C.8 Wastewater chemistry analytes	Monitor, manage and report in accordance with the WWMP and list	Transparency

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
			as per CoP C.8 Wastewater chemistry analytes	
	Wastewater management practices	Rank the following: Avoid Reduce Reuse Recycle Treatment Disposal	C.3.1 Waste management hierarchy C.7.1 Wastewater management plan	Transparency
	Drilling fluids	Quantity Quality Radioactivity	B.4.10.2 Drilling fluids – Mandatory requirements Total volume of hydraulic fracturing fluid pumped Analytes and method for drilling waste assessment – Table 9 BTEX levels in water used for stimulation and drilling fluids Radioactivity from NORMs to determine if the waste is classified under the Radiation Protection Act 2004 (NT)	Control measures must be implemented to minimise the interactions of wildlife, stock, and human receptors with drilling fluid.
2. Operational performance	Above ground Closed Tanks	Volume transferred into each tank. Percentage in relation to wastewater in evaporation ponds Evaporation rate	Water and wastewater tracking and reporting requirements. C.7.1 Wastewater management plan	Promote transparency, accountability, and continuous

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
				improvement in the industry's waste management practices.
	Evaporation ponds	Number of evaporation ponds per region and per operation Volume of wastewater evaporated/tank/operation Estimates for evaporation rates from each tank	Water and wastewater tracking and reporting requirements.	
	Trucks	Frequency Description of waste Volume of waste Costs for transportation/year/operation-region	Water and wastewater tracking and reporting requirements.	Promote transparency, accountability, and continuous improvement in the industry's waste management practices.
	Accidental Spills	Spill incidents – total number/year Spill volumes Minimum freeboard for treatment infrastructure to accommodate total rainfall anticipated	C.7 Mandatory requirements for management plans for wastewater and spills A.3.8 Containment of contaminants Volumes of any spills of water or wastewater	Best practice – linked to WWMP and spill management strategy. Best practice – emergency plan Possible risk – surface spills, infiltration in the ground from the reserve pits or tanks, leaks from pipes, and effects on human health due to exposure to the chemicals, brine and natural radioactive material
	Air emissions	Methane emission from drilling, completion, and natural gas production operations/year Report total volume of methane emitted per volume of natural production (methane released to the atmosphere as a percentage of total natural gas produced) for each calendar year, including the emissions (i.e. volume of methane emitted from drilling, completion, and production) and natural gas production (i.e. total volume of natural gas produced)	D.4 Regional methane monitoring D.5.1 Methane Emissions Management Plan (a) pre-exploration and pre-operation baseline assessments, (b) routine periodic air monitoring, (c) leak management, detection and repair, (d) venting and flaring, other emission sources from gas	Indirect measure of other volatile organic compounds. Best practice – leak detection and repair to manage this issue.

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
			production infrastructure and (f) reporting requirements.	
	Treatment	Current practices Innovative technologies in use	C.7.1 Wastewater management plan	
	Well integrity and fracture containment	Total number and percentage of wells where cement evaluation logs or equivalent tests were performed (by shale play or other reporting area); percentage to be 100%	Part B – Well Operations Well operations management plan Comply with ISO 16530- 1:2017 Well integrity - Part 1: Life cycle governance	Potential risks: deep-well injection could induce earthquakes and cause well casing failure. Casing failure or induced fractures in the rocks could serve as pathway for HF fluid migration into water resources
	Recycle and reuse	Volumes of water planned to be, and ultimately, reused in petroleum operations including drilling and hydraulic fracturing Any options in practice Irrigation Within process For livestock Amount of wastewater used for each purpose. For irrigation – electrical conductivity and sodium adsorption ratio (SAR) of wastewater as an indicator For livestock –TDS of wastewater Dust suppression- SAR and TDS Risks and liabilities from potential uses outside gas industry (Ground Water Protection Council, 2019)	B.4.13.3 e Water used in hydraulic fracture stimulation operations should be recycled for reuse wherever reasonably practicable Recycling and re-use of all fluids should be maximised and the off-site transport and disposal of fluids should be minimised.	Promote transparency, accountability, and continuous improvement in the industry's waste management practices.

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
	Other uses of wastewater	Dust suppression – volume of water and wastewater used Construction water – volume of water and wastewater used	Volumes of water and wastewater used for other purposes including dust suppression and construction water;	
3. Social license to operate/Social impact and Safety	Relationship with local communities	Community engagement/year Number of complaints/year Trust – survey methods? Cultural values in relation to Aboriginal land, ecological values for pastoral land and other related values	Environment Management Plan	Secure community consent – establish community engagement process and third-party conflict resolution mechanisms Reduction of noise, traffic
	Legal	Fine penalties Legal cases – shutdowns orders EPA intervention	B.4.14 Workover and Intervention A program for monitoring and reporting on the effectiveness of mitigation measures for avoiding wildlife, stock and human interactions	Disclose information Activities are sustainable, environmentally responsible, and compliant with regulations
	Health and safety	Incident rates Injuries/year Region-operation-based information Chemical use material safety data sheets The safe handling of any hydrogen sulfide encountered during well operations. Segregating areas for chemical storage and handling from the rest of the well site Safety equipment access and repair Safety meetings frequency Training of workers	Products should be chosen, stored, and used at concentrations that minimise the risk to health and safety and environmental harm. Refer to additional references 1-5	Contractor training Activities are sustainable, environmentally responsible, and compliant with regulations.

Wastewater KPI	KPI	What to measure and when to measure?	Link with NT Codes of Practice	Notes
		Health, safety and environment audits – frequency Safety violation reporting		
4. Economic performance	Cost	Capex and opex costs of current and alternative potential options, cost options, cost/year for a given area, including: Electrical-energy Pipeline Licensing and permitting Site development and closure/remediation at decommissioning Chemicals Monitoring and testing in proportion to gas production? Labour Treatment and distribution capital works Treatment consumables and running costs Transport and handling to reach alternative user vs treatment Ratio of budget for exploring novel technologies	No direct link but influences environmental, social and operational decisions that are part of CoP	Promote transparency, accountability, and continuous improvement in the industry's waste management practices.

5.3 Discussion

The KPIs developed have been grouped into four categories as outlined in Figure 8.

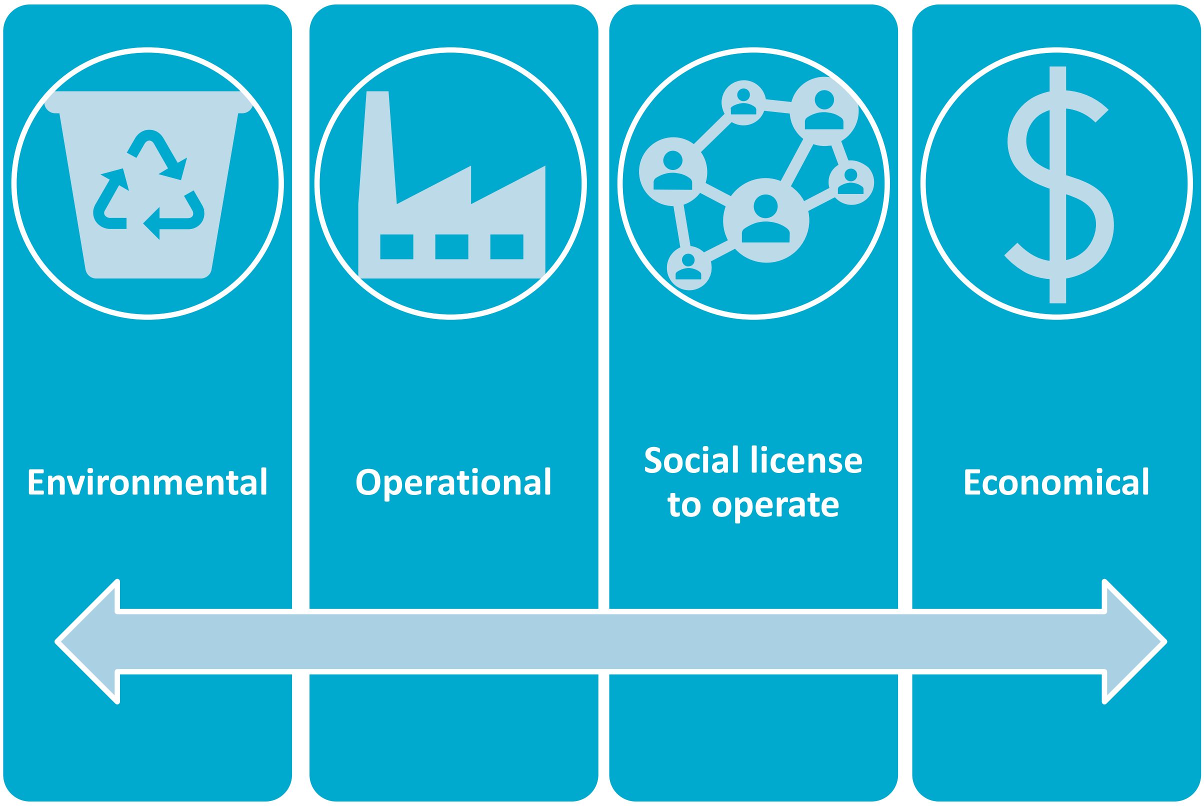


Figure 8. Categories for KPIs for water management

These KPIs have been linked to CoP (Government of Northern Territory, 2019) and will assist in managing water in shale gas operations because they provide a framework for measuring the success of waste management practices and identifying areas for improvement. By measuring factors such as water usage, wastewater treatment, and spill prevention, operators can identify opportunities to reduce their environmental impact, conserve resources, and enhance their social license to operate. The holistic approach incorporating the consideration of balancing community/social, and environmental benefits/outcomes can be only achieved through site-specific data. The KPIs for such criteria have been developed, but they need to be tested based on site-specific information.

The Analytical Hierarchy Process (AHP) method will be applied to prioritise the performance indicators and to develop a framework tool for the application of a holistic approach incorporating technical (treatment, reuse options), environmental (water quality and quantity) and economic analysis (treatment costs, operational costs) using MCDA approach. Please refer to Chapter 7 for the detailed assessment.

6 Wastewater treatment options analysis

6.1 Introduction

This section of the report outlines the treatment options available to achieve the nominated wastewater KPIs. This involved the following steps:

1. Determine the treatment options to achieve the KPIs.
2. Conduct SWOT analyses of treatment options, including water use, infrastructure costs, operational costs, energy consumption, social acceptability, sustainability, waste generated and water quantities. Examine centralised versus decentralised treatment approaches, and single industry versus multi-industry approaches.
3. Document end-use water quality specifications and requirements for categories of beneficial reuse
4. Perform economic feasibility assessment of the treatment technologies based on the infrastructure establishment and operational costs
5. Identify major environmental and social the barriers for the implementation of the treatment technology
6. Address and knowledge gaps, including those associated with data deficiencies
7. Ascertain infrastructure treatment costs for industry trajectories.
8. Incorporate monitoring for water quality and water quantity at process and treatment stages
9. Confirm local water qualities with industry or contractors, collecting new samples if necessary.

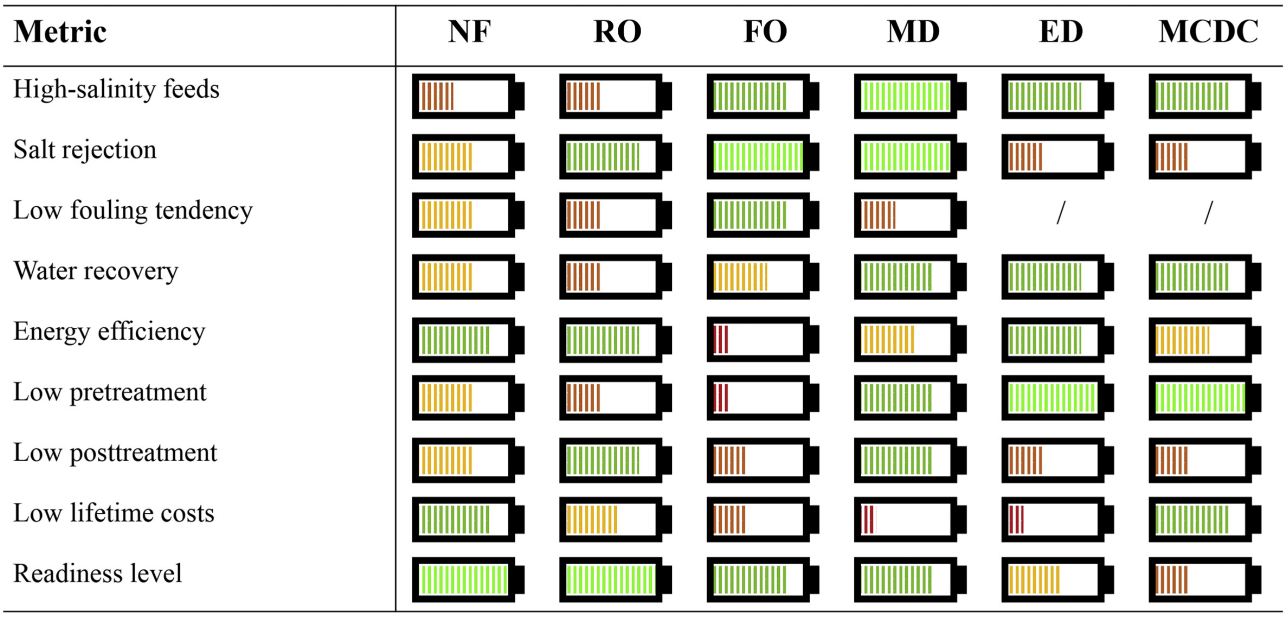
6.2 Technical feasibility of treatment options

Shale gas development in NT is at the exploration stage. Wastewater treatment ponds/tanks are used onsite as the primary waste treatment method to reduce wastewater volumes prior to offsite disposal. Internationally, there are various membrane technologies in use to improve wastewater qualities for reuse. Membrane fouling, lack of full-scale experience and high energy consumption are primary challenges. No single technology is likely to result in the effluent requirements for discharge or re-use (outside direct hydraulic fracturing reuse). Membrane technologies for shale gas internationally include forward osmosis and ultrafiltration/membrane filtration, followed by membrane distillation, electrically driven nanofiltration/reverse osmosis (Table 3). Biologically active membranes are rarely used as a treatment option.

This project undertook a detailed review of treatment options. Evaporation is the most suitable and safest method to reduce the volume of wastewater requiring treatment prior to offsite disposal. Wastewater treatment ponds/tanks are used onsite as the primary waste treatment method to reduce wastewater volumes prior to offsite disposal.

Reverse osmosis (RO) and electrodialysis reversal (EDR) are the most widely used membrane desalination technologies for wastewater treatment. However, these methods offer limited economic suitability to water with mid-range TDS concentrations (less than 40,000 mg/L). Moreover, membrane swelling may occur in both EDR and RO due to the presence of hydrocarbons and solvents. Membrane systems may be economic for producing freshwater if the shale water being treated is lower than 40,000 mg/L total dissolved solids (TDS), representing approximately 4% salt and 96% water.

Table 3. Qualitative comparison of membrane technologies (Chang et al., 2019). NF: Nanofiltration; RO: Reverse Osmosis; FO: Forward Osmosis; MD: Membrane Distillation; ED: Electrodialysis; MCDC: Microbial Capacitive Desalination Cell.



Wastewater management practices are often driven by the economics and logistics of disposal options, but with gas expected to maintain a significant role in our energy systems for decades, new strategies will be crucial to minimising environmental and social impacts. There is a trend In multi-well pad operations overseas to re-use flowback and produced waters in subsequent hydraulic fracturing operations, in 'internal reuse' (Pepper et al., 2018). The internal reuse minimises the wastewater environmental impact and treatment costs while reducing the need for fresh water as fracturing fluid. However, the accumulation of high concentrations of dissolved solids can lead to operational problems.

Wastewater reinjection back into shales can also be explored. However, the HF Inquiry Recommendation 7.9 states:

> *That prior to the grant of any further exploration approvals, the reinjection of wastewater into deep aquifers and conventional reservoirs and the reinjection of treated or untreated wastewaters (including brines) into aquifers be prohibited, unless full scientific investigations determine that all risks associated with these practices can be mitigated.*

The project evaluated the technical feasibility of various treatment options based on pre-treatment requirements, technology readiness, reliability, flexibility, scalability and mobility.

- **Pre-treatment requirements:** In the context of wastewater treatment, pre-treatment refers to the initial stage of processing that involves the removal of large solids, oil, and grease from the wastewater. Pre-treatment is necessary to prevent these materials from clogging or damaging the downstream treatment equipment. Pre-treatment requirements refer to the standards that must be met for the pre-treatment process to be effective.
- **Technology readiness:** Technology readiness refers to the level of development and readiness of a particular wastewater treatment technology to be deployed at scale. A technology that is considered to be "readiness level 9" is fully developed, tested, and demonstrated to be effective in real-world conditions.
- **Reliability:** Reliability in wastewater treatment refers to the ability of the treatment system to function consistently and effectively over time. Reliable wastewater treatment systems are essential for meeting regulatory requirements and preventing environmental harm.
- **Flexibility:** Flexibility in wastewater treatment refers to the ability of the treatment system to adapt to changing conditions, such as changes in wastewater flow rates or contaminant levels. A flexible treatment system can adjust to these changes without compromising treatment effectiveness.
- **Scalability:** Scalability in wastewater treatment refers to the ability of a treatment system to be scaled up or down in size to meet changing needs. A scalable treatment system can accommodate increased or decreased wastewater flow rates or changes in the level of contaminants in the wastewater.
- **Mobility:** Mobility in wastewater treatment refers to the ability of the treatment system to be moved to different locations as needed. A mobile treatment system can be particularly useful in remote or temporary locations where a fixed treatment system is not feasible or cost-effective.

Treatment options were scored high, medium and low based on these criteria. Table 4 summarises categorisations for technical feasibility of different treatment technologies. Pre-treatment requirements are generally high for wastewater treatment using membrane technologies. In contrast, the evaporation pond and thermal processes do not require any pre-treatments steps (Table 5 and Table 6).

Table 4. Categorisation and scoring used for technical feasibility of various treatment options

Pre-treatment requirements	Solids removal, dissolved metals/hardness reduction, organics/nutrients/hydrocarbons removal		
Technology readiness / Track record	Commercially available, frequently implemented	Commercially available, infrequently implemented	Not commercially available, currently in development
Reliability / Operability	Low complexity, high reliability, high operability		High complexity, low reliability, low operability
Flexibility - Feed quality or wastewater quality	Able to accept and successfully treat a large range of water quality and flows without process changes	Able to accept and successfully treat a large range of water quality and flows, however, process changes (such as turndown or lowered treated water quality) may result	Unable to accept and successfully treat a large range of water quality and flows without process changes
Flexibility: scalability	Able to quickly add additional capacity at a low cost	Can add additional capacity but it may be complex, take a long time and/or be costly	Unable to add additional capacity, apart from the addition of a separate new plant
Flexibility: mobility	Able to be easily transport from site to site (i.e. truck-based, containerised / skid-based with minimal interconnections/utility requirements)	May be transported from site to site as skid-based or containerised, but is heavily dependent on separate utilities	Cannot be transported from site to site

Table 5. Technical feasibility of pond-based and thermal treatment technologies

Technology type	Technology name	Pre-treatment requirements	Technology readiness / Track record	Reliability / Operability	Flexibility :feed quality or water quality	Flexibility scalability	Flexibility: mobility
Pond-based	Solar evaporation ponds – Standard	Low	High	High	High	High	Low
	Solar evaporation ponds – Enhanced evaporation	Low	High	High	High	High	Low
	Concept tank for evaporation	Low	High	High	High	High	Low
Thermal Process	Vertical falling film evaporator / brine concentrator	Medium	High	Medium	Medium	Low	Low
	Forced circulation crystalliser	Medium	High	Medium	Medium	Low	Low
	Submerged combustion* (uses waste gas, i.e. free gas)	Low	High	Medium	High	Medium	Medium
	Submerged combustion (no waste gas)	Low	High	Medium	High	Medium	Medium
	Small-scale forced circulation crystalliser	Medium	High	Medium	Medium	Medium	Low

*Submerged combustion is a method of heating a liquid by direct contact of the flame from a burner, which projects the hot gases of the flame directly into and at any depth below the surface of the liquid (Kobe et al., 1933).

Table 6. Technical feasibility of pond-based and thermal treatment technologies

Technology type	Technology name	Pre-treatment requirements	Technology readiness / Track record	Reliability / Operability	Flexibility :feed quality or water quality	Flexibility scalability	Flexibility: mobility
Membrane process	Standard recovery RO	High	High	Medium	Low	Medium	Medium
	High recovery RO	High	High	Medium	Low	Low/Medium	Low
	Very high recovery RO	High	Medium	Low	Low	Low	Low
Novel / Hybrid Process	Membrane distillation	High	Low/Medium	Low	Low	Medium	Medium
	Humidification dehumidification	Medium/High	Low/Medium	Medium	Medium	Medium	Medium
	Forward osmosis (Gradient-type using NaCl draw solution)	Medium/High	Low/Medium	Medium	Low/Medium	Medium	Medium
	Forward osmosis (Standard)	Medium/High	Low	Medium	Low	Medium	Medium
	Solvent extraction process	Unknown	Low	Unknown	Unknown	Unknown	Unknown

6.3 Economic feasibility of treatment options

Estimating costs of other treatment technologies include:

- Capital cost estimation: This method involves estimating the cost of building and installing a treatment system, including equipment, construction, engineering, and other associated costs.
- Operating cost estimation: This method involves estimating the cost of operating a treatment system, including labour, energy, chemicals, maintenance, and other operational expenses.
- Life cycle cost analysis: This method takes into account both the capital and operating costs over the entire lifespan of a treatment system, including the cost of maintenance, repairs, replacements, and disposal at the end of its useful life.
- Comparative cost analysis: This method involves comparing the costs of different treatment technologies to determine the most cost-effective option based on performance, reliability, and other factors.
- Cost-effectiveness analysis: This method compares the costs of a treatment technology to its environmental benefits and the potential impact on public health to determine its overall cost-effectiveness.

These methods can be used individually or in combination to estimate the costs of various treatment technologies and help in making informed decisions regarding wastewater treatment options.

6.3.1 Infrastructure treatment costs for industry trajectories

Economic feasibility of the treatment technologies can vary depending on the different level of development of the industry as described in the Inquiry and other analyst reports (Table 7). Deloitte identified in their economic analysis, that even if the Beetaloo basin becomes economic to develop, the related infrastructure is at risk of becoming fragmented and therefore inefficient and uncoordinated, adding costs to production that could be decisive in a competitive market (Deloitte, 2020). They further recommend that a wastewater characterisation study be undertaken to assess potential for a treatment facility to be located at Katherine, proposing a capital cost value estimate of $28m (Deloitte, 2020). It is uncertain at what stage of industry a centralised facility would become economic; this point is further considered in the economic analysis below.

Experienced engineering wastewater consultants evaluated the economic feasibility to industry of various treatment options .

Table 7. Development scenario projection of shale gas industry in the Beetaloo region (*na not applicable)

Development scenario	KPMG, GHD and RISC report 2019* (Source: Deloitte (2020))	Fracking Inquiry 2018 Chapter 13.3.4.3 pp351 (Source: Pepper et al. (2018))
Baseline/ Nil	na	No further expansion
Low	na	Shale Calm ; exploration only, failure to commercialise
Medium	Low – 159 TJ/day / 58 PJ p/a	Shale Breeze; 36-90 PJ per annum
High	na	Shale Wind; 150-315PJ per annum
Very High	Mid – 1,562 TJ/d or 569 PJ p/a	Shale Gale; 365+ PJ per annum
Extreme	High – 3,300 TJ/d or 1,200 PJ p/a	*NA/No relevant category.*

Capex and opex costs of current and alternative potential options were assessed at all industry trajectories of Breeze, Wind, and Gale scenarios, including:

- Energy costs – usage as $ per volume (e.g. KL/ML/GL), or kWh per volume, where cost per kWh is also reported
- Pipeline costs – $ per km
- Licensing and permitting costs – by logical units
- Site development and closure/remediation costs at decommissioning – by logical units
- Chemical costs – $ per volume
- Cost for monitoring – costs of testing and monitoring – in proportion to gas production for different options. If not known then estimated on logical units
- Labour costs of varying treatment options
- Treatment consumables and running costs
- Transport and handling costs to reach alternative user vs treatment cost
- Treatment and distribution – capital works costs
- Any additional relevant costs that determine technology choice or feasibility
- Consultant knowledge/industry experience of ratio of budgets for exploring novel technologies.

Cost of various treatments were also calculated based on the projected industry development scenarios in the Beetaloo Basin. TDS is highly variable in wastewater and the cost per cubic metre of hydraulic frac flowback fluid at Jackson facility is $0.10 - $0.95/L (Table 8), indicating a broad range in costs for possible economically competitive alternative treatment options.

The Lang Factor method is a commonly used technique to estimate the total capital cost of a process plant. It is based on a ratio of the total cost of creating a process within a plant to the cost of all major technical components. The method was first introduced by H. J. Lang in the 1940s and has since been widely used in the process industries. In the Lang Factor method, the total cost of a process plant is estimated by multiplying the cost of all major technical components by a factor known as the Lang Factor. The Lang Factor is typically estimated based on historical data for similar process plants and can vary depending on factors such as plant size, process complexity, and location. The Lang Factor method was used for capital and operating costs. Lang Factor is an estimated ratio of the total cost of creating a process within a plant to the cost of all major technical components. It is widely used in industrial engineering to calculate a plant's capital and operating costs. High score was given to Lang Factor 0.9-1.0, Medium score to 0.7-0.9 and Low score to 0.5-0.7.

Table 8. TDS-dependent wastewater disposal costs

TDS levels (mg/L)	Rate/Litre (AUD$) *
0 – 50,000	$0.08
50, 000 – 100,000	$0.18
100,000 – 200,000	$0.65
>200,000	$0.95

*Prices excludes GST

Centralised treatment plants typically have higher capital costs but can offer economies of scale, with the potential to treat larger volumes of wastewater and achieve lower treatment costs per unit volume. However, they may also face higher transportation costs if the wastewater must be transported long distances to the treatment plant. Additionally, centralised plants may face opposition from communities concerned about the potential health and environmental impacts of trucking large volumes of wastewater to a single location.

Decentralised treatment options, such as on-site or mobile treatment units, may offer greater flexibility and reduced transportation costs. However, they may also have higher per unit treatment costs and may require significant upfront investment in infrastructure, such as pipelines, to transport treated water to reuse locations. Ultimately, the most economically feasible option will depend on the specific circumstances of each shale play, including the volume and quality of wastewater generated, the proximity of potential reuse locations, and the regulatory and community acceptance of different treatment options.

Table 9 and Table 10 summarise the economic analysis results of the treatment options being used or tested in the exploration phase involving evaporation pond, thermal processes and forward osmosis and hybrid. Displayed are results against the 'Wind' development scenario, representing a midpoint scenario to demonstrate proof of concept of likely treatment options for future production. Reusing wastewater in Beetalloo sub-Basin is currently not economically favourable because of the low disposal cost and low volumes of wastewater. However, the rapid development of unconventional gas industry in 'Wind' and 'Gale 'scenarios would result in more intensive water demand, greater wastewater production which may lead to a higher potential of treated wastewater beneficial reuse.

For example, if a company wants to transport and dispose of 1,000 cubic meters (1ML) of flowback water generated from their shale gas operations. The cost of trucking offsite for disposal is estimated to be $330,000. Alternatively, the company could treat the wastewater onsite using a membrane filtration system. The cost of setting up the treatment system is estimated to be $500,000, and the ongoing cost of operation and maintenance is estimated to be $50,000 per year. The treated water can then be reused onsite, reducing the need for offsite disposal. Assuming the treatment system is used to treat and reuse 10,000 cubic meters (10 ML) of flowback water over its lifetime, the total cost of treating the water onsite would be:

$500,000 (setup cost) + ($50,000 per year x 10 years of operation) = $1,000,000

$500,000 (setup cost) + ($50,000 per year x 20 years of operation) = $2,000,000

In this example, treating the wastewater onsite using a membrane filtration system is more expensive than trucking offsite for disposal if the company only needs to dispose of 1,000 cubic meters of water. However, if the company generates a large amount of wastewater over time (for example, in 'Wind' and 'Gale' scenarios described above) and can reuse the treated water onsite, the cost of treating the water onsite may be lower than the cost of offsite disposal in the long run.

Table 9. Economic feasibility of pond-based and thermal processes*

Technology		Economic feasibility			
Technology Type	**Technology name**	**CAPEX - Centralised (Wind Traj - 800 kL/d feed / 4x WTPs)**	**CAPEX - Decentralised (Wind Traj - 80 kL/d feed / 40x WTPs)**	**OPEX**	**Modularity**
Pond-based	Solar evaporation ponds -– Standard	\$0.5-\$2M/Ha (\$10-40k/ML)	\$0.5-\$2M/Ha (\$10-40k/ML)	\$10-30k/Ha/year	High
	Solar evaporation ponds – Enhanced evaporation	N/A	N/A	N/A	High
	Concept tank for evaporation	\$50-200k/ML	\$50-200k/ML	N/A	High
Thermal process	Vertical falling film evaporator / brine concentrator	\$14-42M	\$5-13M	\$12-20/m^3 feed	Low
	Forced circulation crystalliser	\$28-71M	\$9-22M	\$20-30/m^3 feed	Low
	Submerged combustion (uses waste gas, i.e. free gas)	\$21-63M	\$3.3-10M	\$10-20/m^3	High
	Submerged combustion (no waste gas)	\$21-63M	\$3.3-10M	\$40-60/m^3	High
	Small-scale forced circulation crystalliser	N/A	\$10-20M	\$20-30/m^3 feed	Medium

**Qualifications:*

- Organics/oils and greases/hydrocarbons treatment processes not included in this assessment
- Decommissioning costs not included
- Costs provided here to not take into account the coupling of costs between technologies used in series
- Cost estimates provided are order of magnitude level of accuracy (pre-feasibility) and do not take into account specific locations or scenarios

Table 10. Economic feasibility of membrane and hybrid processes*

Technology Type	Technology name	CAPEX - Centralised (Wind Traj - 800 kL/d feed / 4x WTPs)	CAPEX - Decentralised (Wind Traj - 80 kL/d feed / 40x WTPs)	OPEX	Modularity
Membrane process	Standard recovery RO	$2.1-4.2m	$0.33-0.67m	$1.5-3.0/m^3 feed	Medium/High
	High recovery RO	$2.6-5.1m	$0.51-1.0m	$2.0-4.0/m^3 feed	Medium/High
	Very high recovery RO	$4.3-8.6m	$0.90-1.7m	$2.5-5.0/m^3 feed	Medium/High
Novel / Hybrid process	Membrane distillation	N/A	N/A	N/A	Medium/High
	Humidification dehumidification	$17-64m	$3.4-13m	$20-50/m^3	Medium/High
	Forward osmosis (Gradient-type using NaCl draw solution)	N/A	N/A	N/A	Medium/High
	Forward osmosis (Standard)	N/A	N/A	N/A	Medium/High
	Solvent extraction process	N/A	N/A	N/A	Unknown

**Qualifications:*

- Organics/oils and greases/hydrocarbons treatment processes not included in this assessment
- Decommissioning costs not included
- Costs provided here to not take into account the coupling of costs between technologies used in series
- Cost estimates provided are order of magnitude level of accuracy (pre-feasibility) and do not take into account specific locations or scenarios

6.3.2 Beetaloo wastewater transport costs

The route and transport costs for moving wastewater from the Beetaloo Sub-basin to Westrex water treatment facilities were modelled using information provided in Table 11 and Table 12 below. The optimal route was modelled using the TraNSIT road network and transport models (Bruce C et al., 2021; Higgins et al., 2015; Higgins et al., 2017; Navigate, 2018; NHVR, 2019; QDTMR, 2011; Tan et al., 2012). The TraNSIT model provides a ground-up cost for operating the transporter and includes all logistics elements such as loading, unloading, fatigue management and decoupling requirements based on the vehicle access permissions. It uses parameters in the routing including access permissions for the vehicle combination, and other legislated requirements for freight routing as well as road network attributes and limitations.

Table 11. Input data

ATTRIBUTE	VALUE	NOTES
Origin	Daly Waters, NT	Carpentaria Highway NT (-16.4221, 134.1233)
Destination	40742 Warrego Highway, Jackson QLD 4425	Westrex Wastewater Treatment Facility https://www.westrex.com.au/contact-us/ * Mixed salt to Darwin vs liquid wastes to Jackson, Qld.
Wastewater density (kg/L or tonnes /truckload)	1 kg/L up to 1.3 kg/L	Concentrated brine.
Wastewater toxicity/hazardous nature	Elevated salinity/chlorides from geogenic effects (e.g. >100,000 mg/L)	* Currently high variability in appraisal well water qualities. See table 2 following for indicative water quality.
Truck information	Triple 70 tonnes Double 46 tonnes	
Scenarios to run	Shale 'Gale'	Use well numbers start, annual and total, as per Bruce et al 2021
Indicative volume FPW per well	LOW: 25% HIGH: 75%	Currently seeing around 25% in Beetaloo appraisal wells

For this modelling, the origin point is along the Carpentaria Highway NT (-16.4221, 134.1233) in the Beetaloo Basin to a destination point at Westrex wastewater facility along the Warrego Highway, Jackson Qld (-26.6438, 149.6567). The route needed to accommodate a PBS4a/PBS3a tanker combination carrying 73.4 tonnes (56.5Ml) of wastewater at a concentration of 1.3 Kg/L.

The route (Figure 9) is a 2500km trip one-way and is PBS4a (Type 2 road train) access from the origin to just west of Roma where it becomes PBS3a (Type 1 road train) and decoupling would be required for the last 100 km. The path heads west along the Carpentaria Highway to the Stuart Highway, south to just north of Tennant Creek and thence east and south-east via Mount Isa, Cloncurry, Winton, Blackall, and Roma to the destination.

Table 12. Indicative volumes per well

WASTEWATER PRODUCTION STATS	LOW	HIGH	SOURCE
Well Life (years)	20	20	Bruce et al 2021#
Injected water per well	40 ML	40 ML	GBA
Flowback and produced water (FPW) per well	25% of injected	75% of injected	GBA
Evaporation reduction	1.0	1.3	Various industry, literature and govt sources during project

#Bruce et al 2021 used 40 ML/well, based on an assumption of 40 fracture stages per well, and 25% to 75% flow back

The route meets the requirements for hazardous materials transport, should this be required. The total distance is 2,532km with an expected journey time of 37 hours one way including eight hours fatigue management time, thirty minutes decoupling and one hour loading and unloading. The loading and unloading may vary depending on the loading/unloading facilities and technologies. This time and cost could change using other driving strategies such as a two-up driver or tag-out driver, although these alternatives were not modelled.

The total modelled cost for the trip is $19,994 including an empty return trip, approximately $353/kL. As the costs are not price-based, they can be scaled up to provide the costs for the total volume being transported. A single Type 2 road train combination would deliver the equivalent of between two to six wells' worth of wastewater depending on the injected water volume and the flowback percentage achieved.

Our industry survey also sought to evaluate the costs involved in off-site transportation and treatment. The majority of responses confirmed off-site transport cost to be over $0.60/L of wastewater. Based on personal communication it was confirmed that 0.5 ML wastewater will incur disposal cost of $90,000 ($0.18/L) and the transportation costs would be close to $161,000 ($0.33/L).

Such high costs to transport wastewater are anticipated not to be feasible when the industry moves from the exploration phase into the production phase.

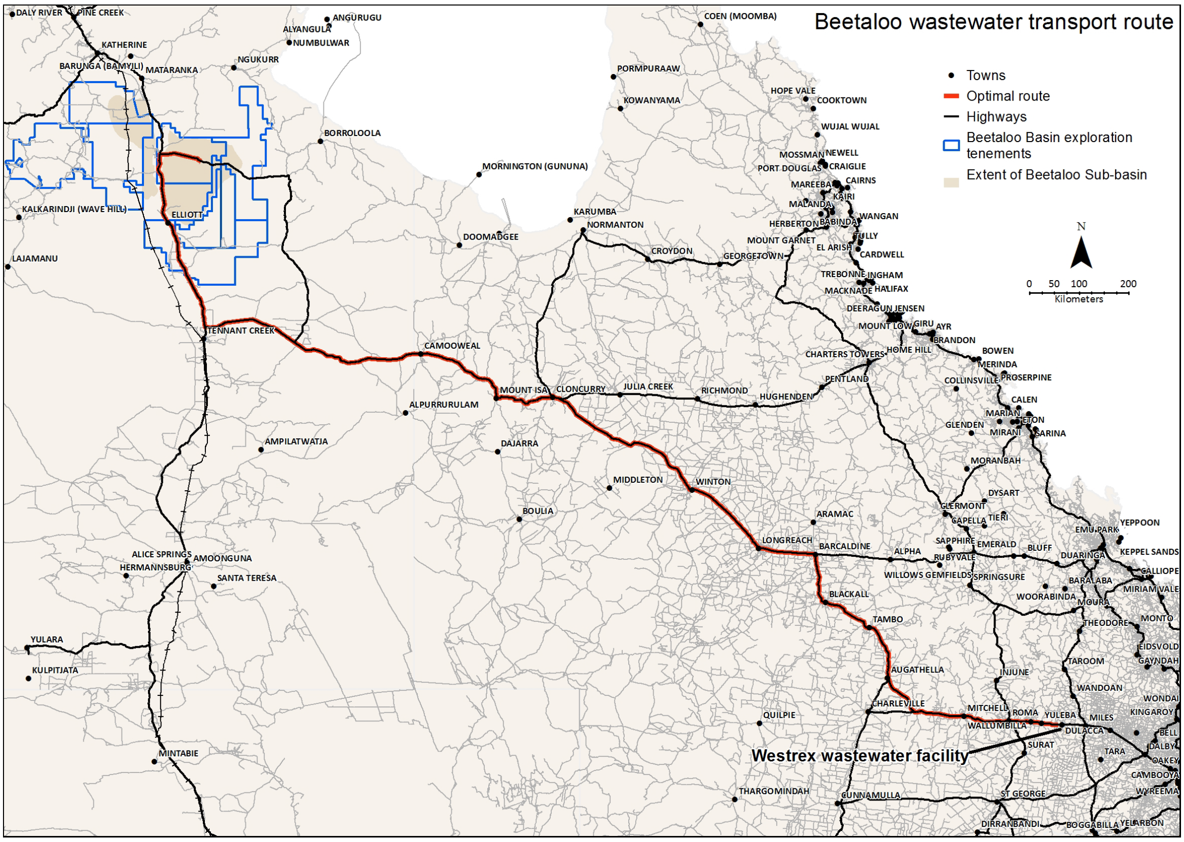


Figure 9.Map of the optimal route based on TraNSIT modelling

6.4 Environmental feasibility of treatment options

Potential harm to natural resources is a commonly used environmental feasibility criterion in evaluating the suitability of a project or activity. Impact on natural resources was considered high in the assessment based on very large footprint and very large waste stream production.

Water reuse readiness can be considered as an environmental feasibility criterion, especially in water-scarce areas or where water quality is compromised. It involves assessing the level of treatment required for the wastewater to be reused safely and effectively. This can include evaluating the quality of the wastewater, its intended reuse, the availability and reliability of treatment technologies, and the regulatory framework governing reuse.

Water re-use readiness was based on evaluation of TDS of wastewater with application of the following ranking:

- High: Able to recover most water at a reasonable quality for re-use (recovery 80-95%; feed water quality salinity dependent)
- Medium: Able to recover some water at a reasonable quality for re-use which may require further treatment (recovery 40-80%; feed water quality salinity dependent)
- Low: Very little water recovery and/or low quality recovered water (recovery <40%; feed water quality salinity dependent.

Energy intensity was classified based on the following ranking:

- High power or gas requirements, no or little energy recovery (>30 kWh/m^3 feed and/or >1000 MJ/m^3 feed).
- Medium ranking for a treatment process was based on: medium levels of power or gas requirements, some energy recovery possible (5-30 kWh/m^3 feed and/or some gas required).
- Pond and membrane processes were classified as low intensity treatments with: lower power or gas requirements, energy recovery possible, may be able to use solar or waste heat (<5 kWh/m^3 feed and/or no gas required).

Table 13 and Table 14 summarise environmental feasibility of various technologies. Based on the assessment, thermal processes have the lowest footprint and the lower production of waste streams compared with the membrane treatment technologies.

Table 13. Environmental feasibility of evaporation pond and thermal treatment-based processes

Technology type	Technology name	Energy Intensity	Water Re-use readiness	Waste stream production	Potential impact on natural resources
Pond-based*	Solar evaporation ponds - Standard	None	None	<5% (solids)	Medium
	Solar evaporation ponds - Enhanced evaporation	None/Low	None	<5% (solids)	Medium
	Concept tank for evaporation	None	None	<5% (solids)	Medium
Thermal process	Vertical falling film evaporator / Brine concentrator	Medium	Medium/High	10-50% (liquid)	Low
	Forced circulation crystalliser	High	Low/Medium/High	2-50% (solid)	Low
	Submerged combustion (uses waste gas, i.e. free gas)	Medium	None	2-50% (liquid/solid)	Low
	Submerged combustion (no waste gas)	High	None	2-50% (liquid/solid)	Low
	Small-scale forced circulation crystalliser	Medium	Medium/High	10-50% (liquid)	Low

*Non-evaporation water storage allows good level of treatment in terms of offgassing, biological treatment and hardness/metals settling in for standard solar evaporation ponds and concept tank treatment.

Table 14. Environmental feasibility of different membrane and novel/hybrid treatment processes.

Technology Type	Technology Name	Energy Intensity	Water Re-use Readiness	Waste Stream Production	Potential Impact on Natural Resources
Membrane process	Standard recovery RO	Low	Medium/High	20-50% (liquid)	Medium
	High recovery RO	Low	High	10-20% (liquid)	Medium
	Very high recovery RO	Low	High	5-10% (liquid)	Low
Novel / Hybrid process	Membrane distillation	Low/Medium	Medium/High	20-50% (liquid)	Low/Medium
	Humidification dehumidification	Low/Medium	Low/Medium/High	2-50% (liquid/solid)	Low/Medium
	Forward osmosis (Gradient-type using NaCl draw solution)	Medium	Medium/High	20-50% (liquid)	Low/Medium
	Forward osmosis (Standard)	Medium	Medium/High	20-50% (liquid)	Low/Medium
	Solvent extraction process	Unknown	Unknown	Unknown	Unknown

6.5 Social feasibility of treatment options

Key studies into onshore gas development have identified the main social impacts (Allen, 2017; Deloitte, 2020; Moffat et al., 2017). Table 15 notes how those key social impacts might be factored into wastewater treatment decisions made by developers of onshore gas.

Table 15. Social impacts and potential mitigating actions associated with shale gas development (Based on Allen (2017); Deloitte (2020); Moffat et al. (2017))

Social aspect	Onshore gas industry general – concerns and recommendations	Wastewater treatment – concerns and recommendations
Health and medical	Social impact assessment required to assess impact on health services of increased workforce Health clinics need be increased	Community may be concerned about health impacts of transport of wastewaters into centralised facility if it's in a township
Roads	Governments should expedite key shared trunk road improvements	Truck volumes of concern either for transport to local centralised facility (e.g. through town if in a town) or to Queensland, given volume and distance. Risks are greater over longer distances (spills, road accidents).
Waste	Solid waste volumes of concern, associated with small regional facilities Waste management capacity assessments and upgrades in key localities including Katherine and Darwin (esp. for listed wastes)	Solid waste (drill cuttings) unlikely to be of concern – low volumes can be treated onsite. However, the presence of NORMs may raise concerns. Final disposal of brines or residues from treatment processes likely to be listed wastes
Employment and skills	Low-skilled local people don't get employment from projects Ensure that skill development for local people that would support longer-term job opportunities are included.	Centralised NT water treatment facility likely to support local technical jobs in a region dominated by low-skill industries and few economic industries
Income inequality	Community concerned about exacerbating rising income inequality; want benefits distributed	Options that treat wastewater in the NT will be more favourable. Consider skill level of treatment options.
Social licence to operate	Community need for acceptance of new industry, and it being well regulated	Community acceptance of wastewater treatment options will require best possible environmental and safety outcomes Community may not accept reuse of wastewater from onshore gas for particular industries, even if deemed safe (e.g. food production)

6.6 Summary of barriers to Implementation

Table 16 summarises key barriers for implementation of treatment and reuse technologies.

Table 16. Major economic, environmental and social barriers to the available treatment/reuse technologies

Key performance areas	Literature	Practice
Technical	High chlorides usually associated with other scaling metals; barium, boron, strontium requiring specialist removal Large distances for pipelines to convey water for treatment options if not modular and on-lease or proximate to lease area	Elevated salinity/chlorides from geogenic effects (e.g. >100,000mg/L) Uncertain flowback water quantities and qualities due to early stage of basin development Some experimental treatments not yet at maturity to deploy (may be ready by production phases, however)
Economic	Decentralised/incremental wastewater treatment may contribute to inefficiencies and increase costs. Recommend centralised facility. Very high estimated costs of alternative and novel treatment methods Conventional RO options may provide economies of scale at high volumes	Treatment is expensive to make highly saline water suitable for reuse. Due to early stage of industry development and large uncertainties with volume and water qualities, this is difficult to estimate prior to further well appraisal.
Environmental	High energy consumption for conventional RO Rich wastewaters potentially containing NORMs, high EC, high TDS, presence of metals Company Environment Management Plans on NT Government webpage	Generation of high strength brine, and high energy consumption for some treatments. Potential for rich residuals. Rich wastewater chemistry present, and extreme variability, make it difficult to plan for feed water quality for treatment
Social	Social acceptability of reuse options and treatment options Reinjection flagged as having low acceptability, and insufficient information	Lack of regional end water users. Social acceptance on reuse of treated wastewaters in ‘suitable’ industries
Institutional/regulatory	There are standard beneficial reuse criteria Direct injection back into shale formations requires additional research to confirm low risk prior to becoming an option	Reuse/recycling beneficial reuse criteria are NOT suitable or are incompatible with reuse Direct (re)injection not currently permitted

6.7 Discussion

Shale water management should start with understanding the distinct types of water, their uses, and their volumes. This will enable better management of the project site's water balance to ensure there is sufficient water available when needed that does not exceed the storage capacity.

Evaporation is considered by industry as the most suitable and safest method to reduce the volume of wastewater prior to offsite disposal. Onsite wastewater treatment ponds or tanks currently serve as the primary method to reduce wastewater volumes prior to offsite disposal. Mobile water treatment technologies have become popular in the oil and gas industry due to their flexibility and mobility. These systems can be quickly deployed to drilling sites and can treat wastewater on-site, reducing the need for water transportation and disposal.

Semimobile modular systems are another option that is gaining popularity. These systems offer the benefits of a centralized treatment plant but with the added advantage of mobility. They are typically designed as prefabricated units that can be transported to the site and assembled on-site. This approach offers economies of scale with increased process efficiency and simplified water transportation logistics.

Practitioners need to consider the chemistry, which may include scalants, TDS and NORM. The water chemistry significantly affects the water treatment strategy, as well as informing end-of-life options for the waste byproducts that are left once clean water is removed.

Membrane fouling, lack of full-scale experience and high TDS and energy consumption are challenges associated with application of membrane technologies.

Although there are many water management options available, there is no single best solution. It is important to understand the costs, alternatives, and technical limitations of each option and develop a blended water management strategy to balance costs and risks. Choosing a wastewater treatment process will depend on the uses of wastewater, contaminates to be removed, power requirements, wastewater treatment and on-site treatment options (Figure 10).

Figure 10. Key considerations for wastewater treatment

Economic, social and spatial feasibility of treatment options must be determined, taking into account:

- Community opinion and cultural implications
- Cost of on-site treatment set-up or transport to off-site treatment plants
- Guideline requirements for contaminant levels in treated wastewater for reuse
- Cost and likely volumes for centralised treatment as an option, once more results across the region from appraisal programs are available.

There is still uncertainty about the quality of HF flowback in the Beetaloo, which varies spatially and is highly dependent on target formation. Once a field location moves to appraisal stage, stakeholder will determine the treatment required.

7 Synthesis and decision support framework

7.1 Introduction

As a dry continent, the competition for water is intensifying. There is a pressing need to better manage or reuse wastewater at gas production sites. However, quantifying the effects of onshore gas wastewater management practices is difficult, partly because the wastewater use has the potential for cumulative impacts. Identifying good practice helps site managers adopt more rational and sustainable management solutions . Nonetheless, the optimal selection of water management practices requires the comprehensive evaluation and prioritisation of management options against numerous requirements. It involves multiple criteria decision-making analysis (MCDA) (Zhang et al., 2010).

The project has used MCDA to assess treatment options, due to its successful application in water management in Australia and internationally, and its transparency in dealing with the complexity of multiple stakeholders and triple bottom line analysis (Hajkowicz and Collins, 2007; Petheram et al., 2017). We conducted a multi-criteria analysis and developed a framework tool for the application of a holistic approach incorporating technical (treatment, reuse options), environmental (water quality and quantity) and economic analysis (treatment costs, operational costs) that balanced community benefits.

Multi-criteria decision analysis (MCDA) is a structured approach for measuring the performance of alternatives that are based on multiple attributes, or criteria. The different methods that fall within this category can support the decision analysis process for issues in which more than one criterion—also known as attribute—is simultaneously evaluated. . Various MCDA tools enable the inclusion of relative importance, or weight, for each criterion to be used to rank the performance of themagainst the selected criteria.

These methods can improve the transparency, auditability, and analytical rigor of decision-making processes in complex contexts. Numerous MCDA techniques provide decision makers and analysts with approaches to properly and effectively address decision problems. The selection criteria can include capital cost, operating and maintenance costs, space (footprint) requirement, commercial availability, mobility, and energy demand.

The project has developed a decision support framework that combines many selection criteria, producing efficient treatment trains capable of treating non-traditional waters to the target water quality required for beneficial use or discharge to the environment. Determination of criterion weights is crucial in MCDA. The analytical hierarchy process (AHP) is a popular mathematical method for this purpose. It derives the weights through pairwise comparisons of the relative importance between each two criteria. All weighted criteria can then be aggregated using a weighted combination method (e.g. ordered weighted averaging (OWA), or fuzzy OWA) to generate output ranking(s) from the decision support framework.

This section of the report documents the development of a MCDA framework tool to develop decision support for shale gas wastewater management.

7.2 Methodology

A wastewater treatment train for a water reuse project can be selected based on the end use of wastewater for achieving economic efficiency and environmental sustainability. Such treatment is referred to as fit-for-purpose wastewater treatment. It aims to avoid both over- and under-treatment, constrained by environmental regulations. Water quality depends on the level of water and wastewater treatment, which is dictated by the end use of water.

Section 4 documents the review of treatment options available to achieve the nominated wastewater KPIs (key performance indicators). The technical feasibility of various treatment options were evaluated based on pre-treatment requirements, technology readiness, reliability, flexibility, scalability and mobility and scored high, medium and low based on these criteria.

The initial scope for this phase of the project was to include development of MCDA for all stages of the development life cycle in the Beetaloo. During industry and government consultation combined with assessment of available data during the design phase of MCDA, the project determined that the very nascent stage of onshore gas appraisal would constrain this approach. Data was available on the three wells in the appraisal stages. High variability in water quality and flow data also meant that there is still considerable uncertainty regarding the quantities, qualities and locations likely for wastewater production. This limits the ability to apply the full wastewater framework to broadly optimise the operational, environmental, economic and social criteria across the project life cycle.

Section 5.3 summarised the categorisation on technical feasibility of different treatment technologies. Based on stakeholder feedback, the project team instead applied the treatment module of the framework to assess the technical treatment options available at the appraisal stage of industry, to inform current practice and provide value to government, industry and community at this early stage.

Only a handful of wells have been tested. Therefore, reuse opportunities are limited. Reuse trials are likely to begin once a resource is confirmed and reserves move from contingent to probable and multiple wells per formation are drilled, permitting a reliable characterization of water qualities and volumes requiring treament.

Consequently, reuse options that could be explored in the near future as an industry specific case-study are documented here. The report discusses the beneficial use and optimisation criteria requirements to develop decision support for wastewater management.

7.3 MCDA

The logic of the MCDA methodology is presented in Figure 11. The involvement of stakeholders and the expert team in the whole process is highlighted in the conceptual schema. Detailed discussion follows on each of the key steps.

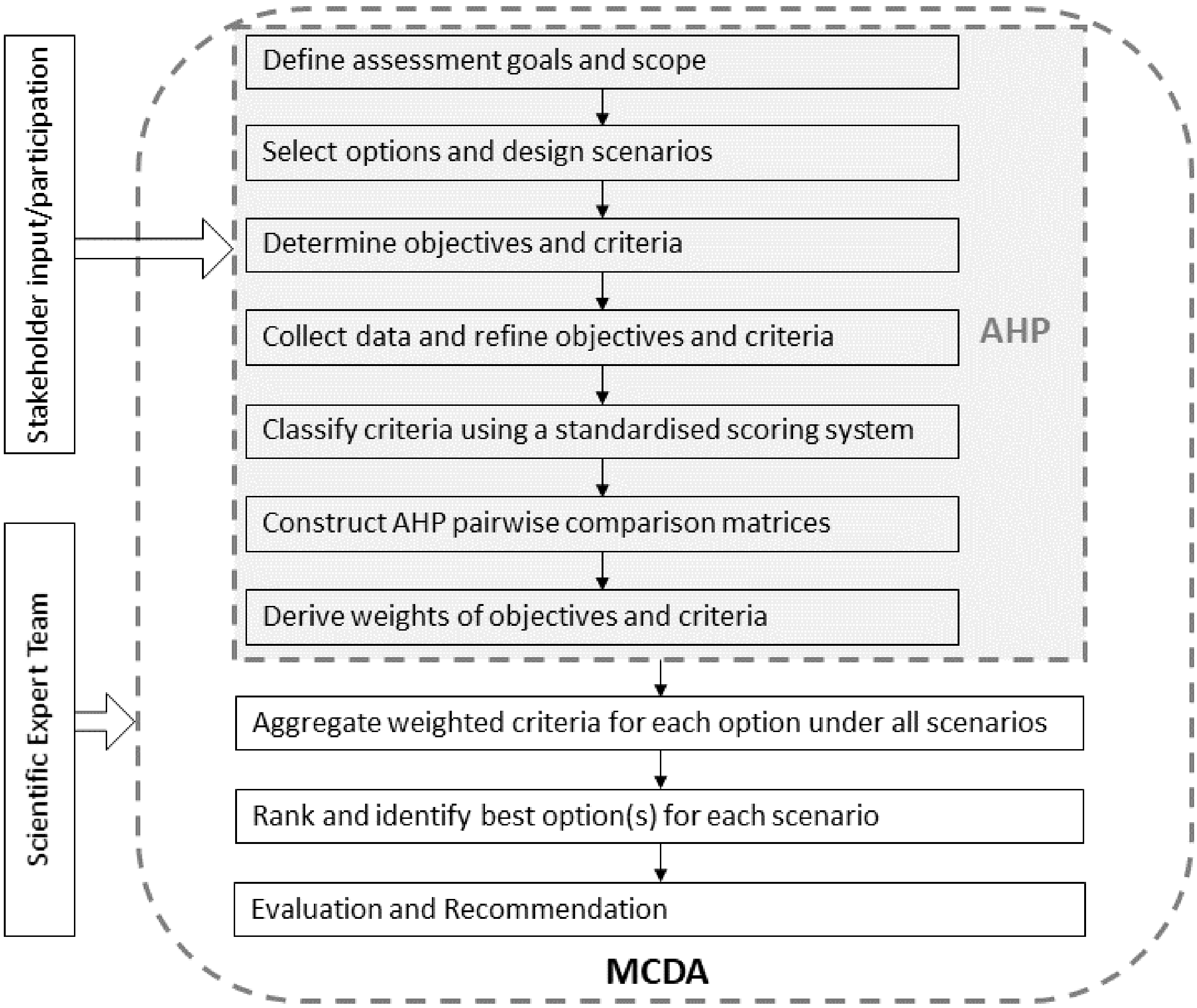


Figure 11. Flowchart of MCDA methodology

7.4 Treatment evaluation options and objectives

Three broad types of treatment options were considered for MCDA (Table 17).

Table 17. Treatment options evaluated in this study

Pond-based	Solar evaporation ponds - Standard clay lined
	Solar evaporation ponds - Standard HDPE lined
	Solar evaporation ponds - Enhanced evaporation
	Concept tank for evaporation
Thermal process	Brine concentrator - Vertical falling film evaporator
	Forced circulation crystalliser
	Submerged combustion (uses waste gas i.e. free gas)
	Submerged combustion (no waste gas)
	Small-scale forced circulation crystalliser
Membrane process	Standard recovery RO
	High recovery RO
	Very high recovery RO
	Humidification dehumidification

The main problem associated with the wastewater produced in shale gas extraction is the high salinity, with TDS concentration increasing after the fracturing operation.

7.4.1 Evaporation pond/tank

Evaporation ponds, lined with quality, high density polyethylene liners, are regarded by the oil and gas industry as an affordable solution for processing production and flow back water. Evaporation techniques are based on the supply of thermal energy to the liquid stream in order to evaporate part of the water, yielding freshwater and brine with a higher TDS concentration.

Current evaporation ponds are based on the following liner condition/types:

1. Geomembrane
2. Constructed clay liners
3. Natural clay (with no liners).

Geomembrane liners are regarded as the most effective based on their potential for reducing leakage compared to that of clay. Clay liners are prone to desiccation cracks that create microstructural pores. The condition may exacerbate with age. Clay lined evaporation ponds are not in use in the Beetaloo region.

Water evaporation driven by solar energy (known as solar evaporation) is widely used in industries. In particular, the solar evaporation ponds are considered as an effective way to produce various salts such as sea salts and lithium salts, and fresh water from seawater and brines. They are also used for brine management in inland desalination plants.

A concept saline effluent management system has following characteristics:

- Multiple concept tanks in series

- Uses renewable solar energy for concentration process
- Reduced upfront and total capital cost
- Incremental storage based on actual not projected water flows

The approximate cost of the 56 ML concept tank (Figure 12) is $2m. This includes a double layer liner and a leak detection system. These tanks can then be relocated for around 65% of the cost, leaving behind only a flat earthen pad.

Figure 12. Concept tank system

7.4.2 Thermal process

Vertical tube falling film/brine concentrator and vapour compression evaporation are effective methods for wastewater treatment because they eliminate physical and chemical treatments, so no chemical sludge is produced, and costs of waste and life cycle are lowered. Figure 13 presents the flow diagram of the brine concentrator evaporator. Once established, they require less maintenance materials and maintenance labour. However, due to high levels of solid salts, the reuse of these materials is difficult. The brine concentrator is being use by the Ranger Mine in NT.

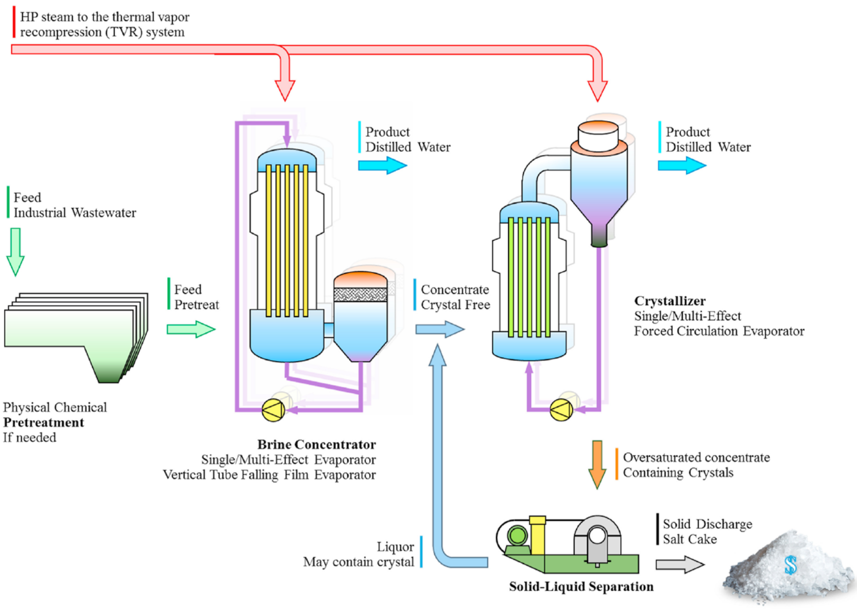


Figure 13. Flow diagram of brine concentrator process (Azimibavil and Jafarian, 2021)

Figure 14 shows the horizontal falling film system for shale gas produced water desalination. The multiple-effect plant comprises several effects of horizontal-tube falling film evaporation and flashing tanks, which are placed in an intermediate way. Horizontal-tube falling film evaporators present numerous advantages – including compact size and easy operation and maintenance – over other evaporation equipment such as vertical-tube falling film and forced-circulation. The horizontal-tube falling film evaporators are widely used due their higher heat transfer coefficients, lower temperature differences and film flow rates, and simpler construction. Other benefits include the ability to deal with non-condensable gases, liquid distribution and fouling problems.

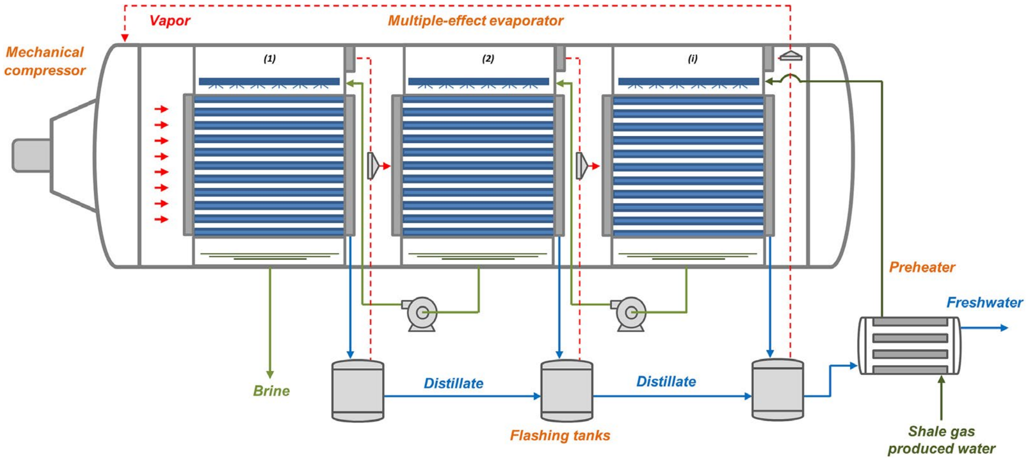


Figure 14. Horizontal falling film proposed for desalination of high-salinity produced water from shale gas production (Onishi et al., 2017)

The forced circulation crystalliser creates a super-saturated solution by evaporating solvent from the saturated solution. The solute of this supersaturated solution cools, forming the crystals. The small-scale forced circulation crystalliser developed by Veolia EVA-LED Process is typically heat-pump driven or steam driven. This system can accept most feed water qualities but may need some pre-treatment to address solids and organics.

Submerged combustion is a method of heating a liquid by direct contact of the flame from a burner, which projects the hot gases of the flame directly into and at any depth below the surface of the liquid (Kobe et al., 1933). This process involves igniting gas or fuel oil in a manner that releases hot combustion product gases below the surface of a liquid, allowing for the energy produced by the combustion to be transferred through direct contact with the liquid. While it is possible for the burner to be submerged, most systems have the burner situated above the liquid level and use a submerged exhaust system. As shown in Figure 15, the exhaust gas is released into the space between the downcomer and draught tube, which results in effective mixing between the hot gas and the liquid and generates strong circulation of the liquid within the tank (Thermopedia, 2011).

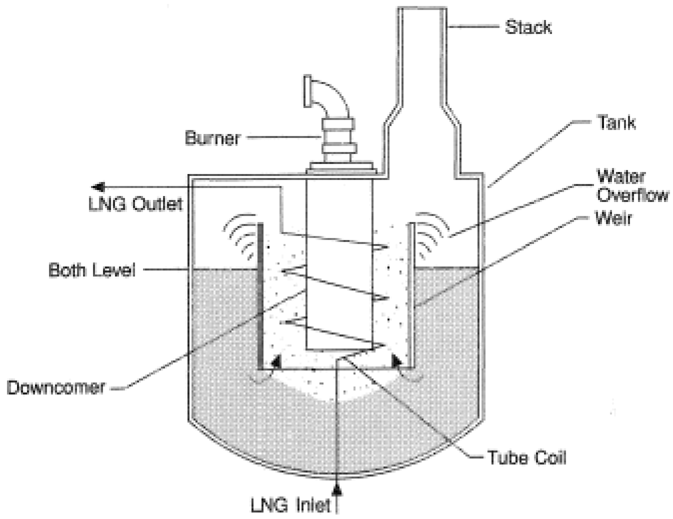


Figure 15. Submerged combustion evaporator (Thermopedia, 2011)

7.4.3 Membrane process

Traditional methods of wastewater management do not satisfy the requirements for treating wastewater in compliance with discharge and reuse standards. Membrane treatment, such as reverse osmosis or distillation is often necessary to remove the salts and radioactive substances before wastewater can be used for agricultural purposes or discharged into surface waters. Such treatment processes are expensive and not economically viable in the exploration phase in Beetaloo Basin.

Multi-use high water recovery process integrates water purification membranes including reverse osmosis and nanofiltration with ion exchange water softening resins. There are a number of configurations that optimise operation and achieve maximum membrane permeate recoveries while eliminating the use of fresh water, sodium chloride and other chemicals needed to regenerate the IX resin. The invention provides process mobility and flexibility that enable selection of optimum process configurations and features to address variability in the influent water quality. This system will not be able to concentrate water above 60,000-100,000 mg/L.

Membrane process involving very high recovery RO uses Osmoflo Brine Squeezer to maximise the recovery of the reject from reverse osmosis plants. The high recovery and very high recovery RO systems are unable to concentrate water above 60,000-120,000 mg/L. The process is sensitive to feed water chemistry and changes. Significant pre-treatment is likely required to deal with solids, organics, oils and greases, and hydrocarbons and recovery may be limited by hardness, metals and silica levels.

Hybrid treating systems, involving a combination of two or more membrane processes, show more efficacy for treating wastewater. For example, a four-step method has recently been proposed by Atoufi and Lampert (2020) that is focused on removing salts from wastewater. The first step, feed softening, reduces the chances of fouling during the membrane processes by adding calcium hydroxide to the sample; large amount of suspended solids can be removed by sand filtration, representing the second step; the third step, based on ceramic membranes, targets removal of oil and gas; the final step employs RO technique with PA-TFC membrane (Atoufi and Lampert, 2020).

The novel/hybrid process including humidification and dehumidification has little history and is not used in the Australian hydrocarbons industry. This hybrid system accepts most feed water qualities but may need some pre-treatment to address solids and organics.

The project evaluated four objective-focused scenarios:

1. equally preferred objective
2. strongly preferred environmental objective
3. strongly preferred economic objective
4. strongly preferred technology objective.

7.5 Criteria selection and scoring for treatment

The selection of wastewater treatment options can be based on several factors, the most important of which is the environmental, technical and economic feasibility of such options (Silva et al., 2020). We analysed options against the KPIs and beneficial use (highly acceptable — no risk and low risk, moderately acceptable — risk, and unacceptable — high risk) and optimisation criteria requirements to develop decision support for wastewater management. This includes the selection of criteria and determination of their thresholds. The KPIs included in this assessment are summarised in Table 18. Qualitative and quantitative classes of criteria for scoring are listed in Table 19.

Table 18. Set of criteria used in this study

Objective	Criteria	
Technology (T)	T1	Pre-treatment requirements
	T2	Readiness / Track record
	T3	Reliability / Operability
	T4	Flexibility - Feed Q or WQ
	T5	Flexibility - Scalability
	T6	Flexibility - Mobility
Environmental (E)	E1	Energy intensity
	E2	Water re-use readiness
	E3	Waste stream production (% solids/liquids)
	E4	Impact on natural resources
	E5	TDS (mg/L)
Economic (C)	C1	CAPEX ($)
	C2	OPEX ($)
	C3	Waste disposal costs ($/KL)
	C4	Modularity
	C5	Waste transport costs

Estimated applicable operating ranges for various technologies in terms of capacities are listed below. All technologies that score high in terms of 'Flexibility – Scalability' (e.g. ponds) are able to be implemented with little cost impacts for a large range of project sizes, whereas the technologies listed below are either not available, more expensive or more complicated at certain size ranges.

- Limited to larger capacities i.e. >~400m^3/d feed capacity:
  - Vertical falling film evaporator / Brine concentrator
  - Forced circulation crystalliser
- Limited to smaller capacities i.e. <~400m^3/d feed capacity:
  - Submerged combustion (no waste gas)
  - Small-scale scraped surface crystalliser
  - Membrane distillation
  - Humidification dehumidification
  - Forward osmosis
  - Solvent extraction process
- Overly complicated at lower capacities i.e. <~100 m^3/d:
  - High recovery RO
  - Very high recovery RO

Disposal costs are dependent on the volume and chemistry of wastewater and size and location of the operation. Disposal wells are used in the US to inject mineralised water produced from oil and gas mining into underground zones for safe and efficient disposal. The deep injection wells are not permitted as disposal or treatment method according to the CoP. Disposal wells typically require three layers of casing to ensure groundwater is protected. The first protection layer is surface casing, involving a steel pipe that is encased in cement reaching from the ground to the base of the deepest usable quality groundwater. Surface casing also acts as a protective sleeve through which deeper drilling occurs. The second protection layer is the production casing, involving a pipe inside the surface casing extending to the well's total depth and permanently cemented in place. Wells may also be constructed with an intermediate casing between the surface casing and the production casing. The third protection layer is the injection tubing string and packer that conducts the injected water down through the production casing to perforations at the bottom of the well to inject the water into an underground formation. The tubing/packer assembly creates an isolated annulus that is monitored to detect any pressure changes that may indicate a leak or other type of mechanical issue and allow the well to be shut down before any harm can occur. E2, the criterion on water reuse readiness, has been addressed within the framework.

7.6 AHP weighting criteria and objectives

The AHP method employs an underlying semantic scale with values from 1 to 9 to rate the relative preferences/importance (Table 20) for two elements (objectives or criteria). The available values for the comparison are the member of the set: (9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9), with 9 representing absolute importance and 1/9 the absolute (Saaty and Vargas, 1991).

This study developed pair-wise comparison matrices at both objective and criterion levels. The comparison matrices for the criterion level are presented in Table 21 (a), (b) and (c). Table 21(a), for example, gives a matrix of criteria corresponding to the technology objective. It assigns a numerical value showing relative importance of each criterion under this objective. Stakeholder consultation regarded T3 (Reliability/Operability) criterion moderately more important than T1 (Pre-treatments), hence a value of 3 was assigned to the corresponding matrix position. The transpose position automatically receives the reciprocal value, in this case 1/3 or 0.33. In summary, the weights for objectives and criteria were calculated (Table 21 (d)) based on the derived matrices for objectives and criteria.

Table 19. Qualitative and quantitative classes of criteria for scoring (H, High; M, Medium; L, Low; N, None)

Treatment Options	T1	T2	T3	T4	T5	T6	E1	E2	E3	E4	E5 (mg/L)	C1 ($M)	C2 ($)	C3 ($/L)	C4	C5
Solar evaporation ponds - Standard Clay Lined	L	H	H	H	H	L	N	N	<5% (solids)	M	250,000	0.375	20,000	0.95	H	H
Solar evaporation ponds - Standard HDPE Lined	L	H	H	H	H	L	N	N	<5% (solids)	M	300,000	1.5	20,000	0.95	H	H
Solar evaporation ponds - Enhanced evaporation	L	H	H	H	H	L	N/L	N	<5% (solids)	M	250,000	1.5	20,000	0.95	H	H
Concept Tank for evaporation	L	H	H	H	H	L	N	N	<5% (solids)	M	250,000	7.5	20,000	0.95	H	H
Brine Concentrator - Vertical Falling Film Evaporator	M	H	M	M	L	L	M	M/H	10-50% (liquid)	L	250,000	8	15	0.95	L	M
Forced Circulation Crystalliser	M	H	M	M	L	L	H	L/M/H	2-50% (solid)	L	250,000	14	25	0.95	L	M
Submerged Combustion (utilises waste gas)	L	H	M	H	M	M	M	N	2-50% (liquid/solid)	L	250,000	6.5	15	0.95	H	M
Submerged Combustion (no waste gas)	L	H	M	H	M	M	H	N	2-50% (liquid/solid)	L	250,000	6.5	50	0.95	H	M
Small-Scale Forced Circulation Crystalliser	M	H	M	M	M	L	M	M/H	10-50% (liquid)	L	250, 000	15	25	0.95	M	M
Standard Recovery RO	H	H	M	L	M	M	L	M/H	20-50% (liquid)	M	50, 000	0.5	2.2	0.18	M/H	L
High Recovery RO	H	H	M	L	L/M	L	L	H	10-20% (liquid)	M	50, 000	0. 75	3	0.18	M/H	L
Very High Recovery RO	H	M	L	L	L	L	L	H	5-10% (liquid)	L	50, 000	1.3	4.2	0.18	M/H	L
Humidification dehumidification	M/H	L/M	M	M	M	M	L/M	L/M/H	2-50% (liquid/solid)	L/M	250, 000	3.2	35	0.95	M/H	L

Table 20. AHP – Scale for pair-wise comparisons

Intensity of Importance	Description
1	Equally preferred
2	Equally to moderately
3	Moderately preferred
4	Moderately to strongly
5	Strongly preferred
6	Strongly to very strongly
7	Very strongly preferred
8	Very strongly to extremely
9	Extremely preferred
Reciprocals	Values for inverse comparison

Table 21. AHP weighting: (a) Comparison matrix for technology criteria; (b) Comparison matrix for environmental criteria; (c) Comparison matrix for economic criteria; and (d) Weights for the four objective-focused scenarios and all criteria derived from AHP.

Criteria	T1	T2	T3	T4	T5	T6
T1	1.00	1.00	0.33	0.20	1.00	1.00
T2	1.00	1.00	0.33	0.20	1.00	1.00
T3	3.00	3.00	1.00	0.50	1.00	1.00
T4	5.00	5.00	2.00	1.00	5.00	5.00
T5	1.00	1.00	1.00	0.20	1.00	1.00
T6	1.00	1.00	1.00	0.20	1.00	1.00

(a)

Criteria	E1	E2	E3	E4	E5
E1	1.00	0.33	0.33	0.20	0.25
E2	3.00	1.00	1.00	0.33	0.50
E3	3.00	1.00	1.00	0.50	0.50
E4	5.00	3.00	2.00	1.00	2.00
E5	4.00	2.00	2.00	0.50	1.00

(b)

Criteria	C1	C2	C3	C4	C5
C1	1.00	1.00	3.00	5.00	3.00
C2	1.00	1.00	3.00	5.00	3.00
C3	0.33	0.33	1.00	4.00	1.00
C4	0.20	0.20	0.25	1.00	0.25
C5	0.33	0.33	1.00	4.00	1.00

(c)

Scenario (Column) / Criteria (Row)	T1	T2	T3	T4	T5	T6	E1	E2	E3	E4	E5	C1	C2	C3	C4	C5
Equal Objective	0.333						0.333					0.333				
Strongly-preferred Environmental Objective	0.143						0.714					0.143				
Strongly-preferred Economic Objective	0.143						0.143					0.714				
Strongly-preferred Technology Objective	0.714						0.143					0.143				
Criteria Weights Applied to All Scenario	0.092	0.092	0.182	0.344	0.204	0.085	0.059	0.145	0.158	0.383	0.255	0.34	0.34	0.136	0.048	0.136

(d)

7.7 Treatment scenario modelling

A wastewater treatment option for a water reuse project can be selected based on the end use of wastewater for achieving economic efficiency and environmental sustainability, referred to as fit-for-purpose wastewater treatment. It aims to avoid both over- and under-treatment, constrained by environmental regulations. Water quality depends on the level of water and wastewater treatment, which is dictated by the end use of water.

The MCDA approach comprises many methods. The project used the AHP-based weighted sum model (Chen et al., 2015).

For an MCDA problem defined on multiple objectives and criteria, if it is assumed that all the criteria are benefit criteria, that is, the higher the values are, the better it is, then total evaluation ranking (when all the criteria are considered simultaneously), denoted as $Rank^{score}$ is defined as follows:

$Rank^{score} = W_T \sum_{t=1}^{n} w_t c_t + W_E \sum_{e=1}^{m} w_e c_e + W_C \sum_{c=1}^{l} w_c c_c$

where:

W_T, W_E and W_C denote the weight of the technology, environmental and economic objective, respectively.

w_t, w_e and w_c denote the weight of the technology criterion c_t, environmental criterion c_e and economic criterion c_c, respectively.

t, e and *c* are the number of c_t, c_e and c_c, respectively; in this project, n = 6, m = 5 and l = 5.

The project aggregated multiple identified treatment options and wastewater reuse criteria. Included were collective evaluation runs using different weighted criteria based on different prioritised options. Generally, the best option is the one with the maximum $Rank^{score}$ value.

7.8 Result ranking

The following category was applied to $Rank^{score}$ (Table 22), which used as simple means to compare viable options and determine the optimum solution.

Table 22. Ranks of MCDA results , 4 being the best option

1	Fair option	
2	Very fair option	
3	Good option	
4	Best option	

7.9 Overall MCDA conceptual model

The MCDA approach is an effective tool to evaluate the environmental effects of different wastewater treatment systems and to evaluate the overall efficiency of economic indicators. Environmental, economic, and social factors should be balanced in the process of achieving successful wastewater treatment. Figure 15 illustrates an overall MCDA framework for wastewater lifecycle management. The KPIs developed should be further tested by considering case studies in the Beetaloo region.

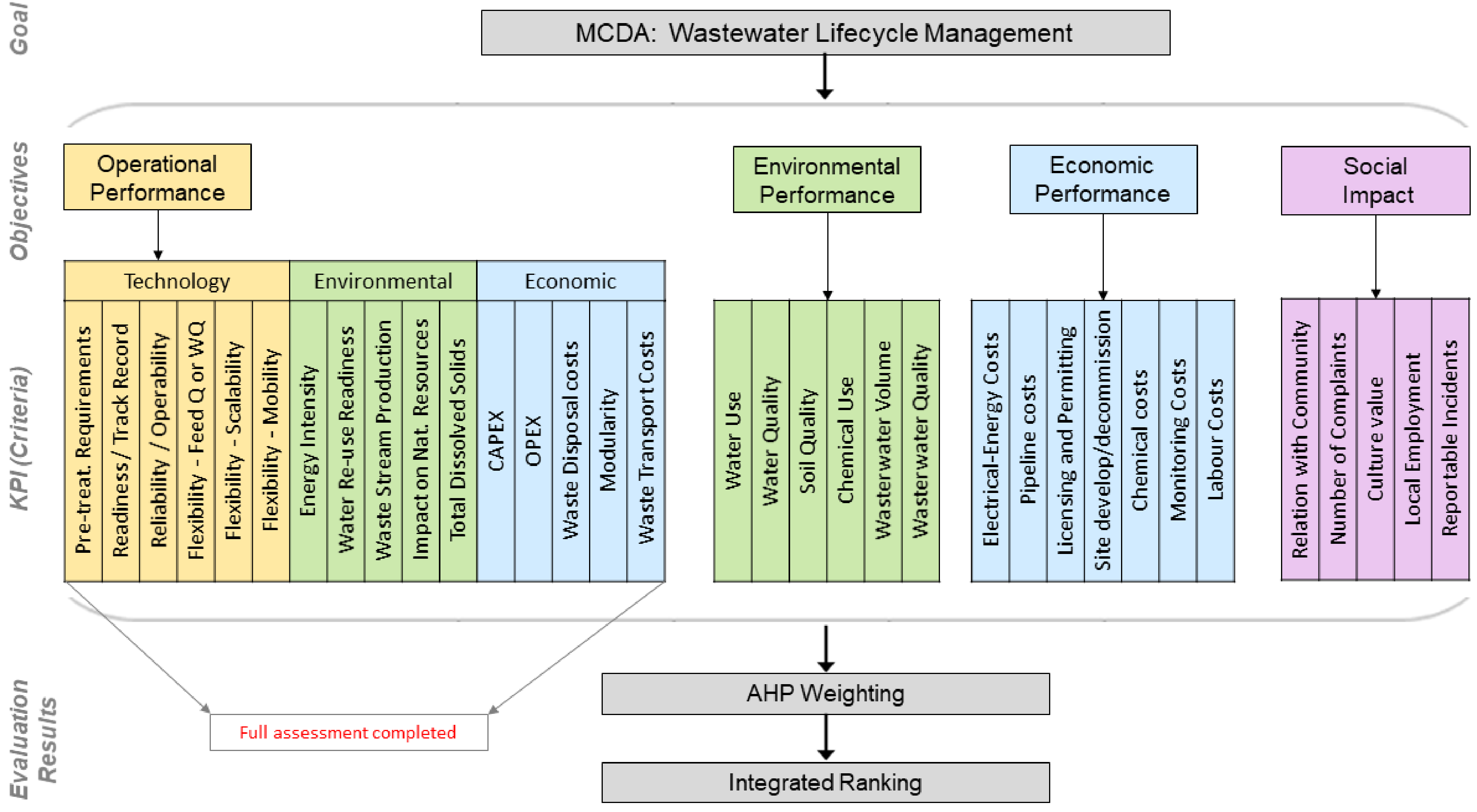


Figure 16. Overall MCDA framework for wastewater lifecycle management

7.10 MCDA framework for treatment options

The project undertook a detailed review of treatment options and used the detailed MCDA to assess treatment options for best value now. Technology, environmental and economic criteria were evaluated based on the KPIs (Figure 16).

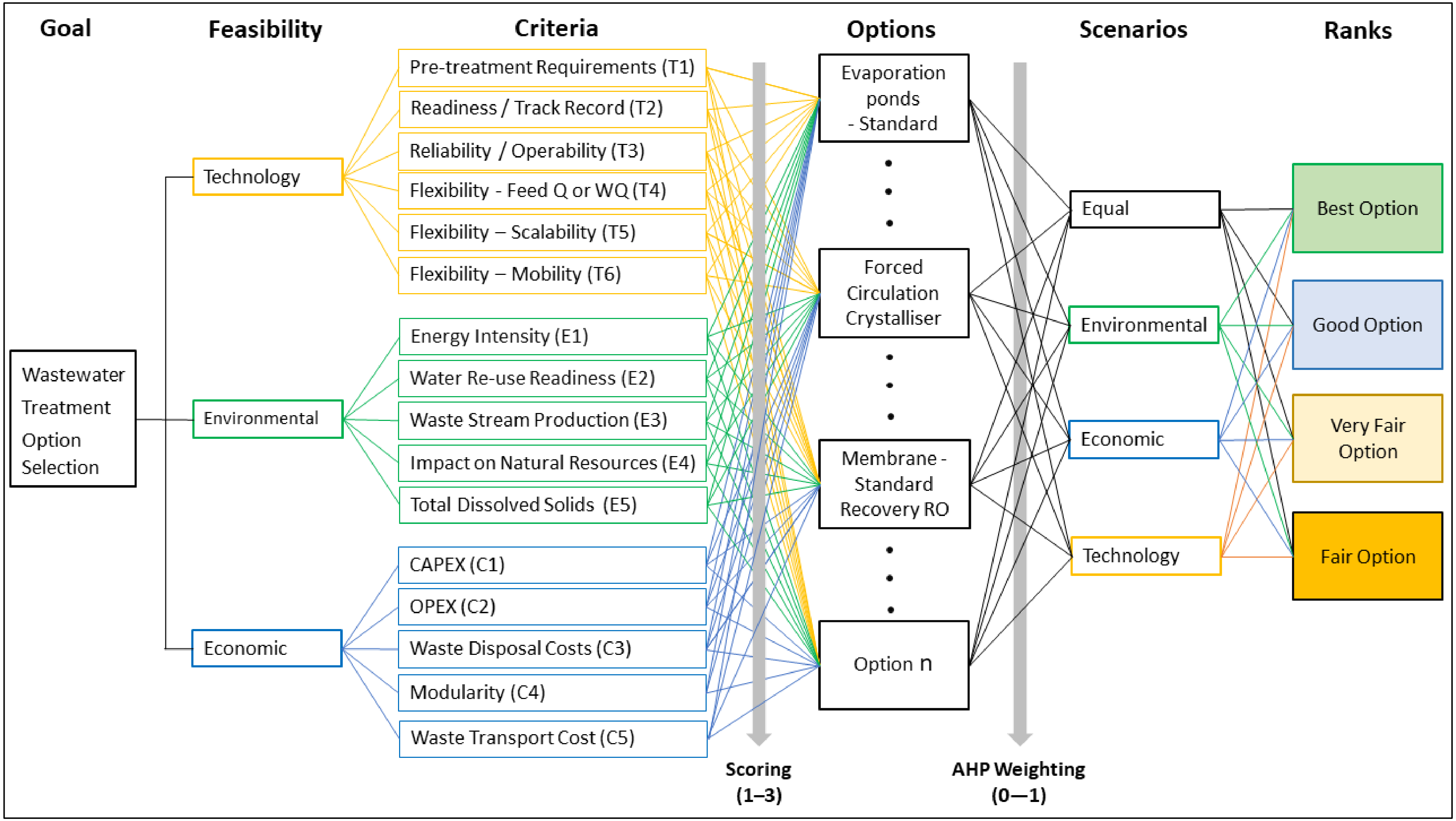


Figure 17. MCDA wastewater treatment option evaluation framework

7.11 Wastewater treatment scenario results

The final results of treatment option evaluation are shown in Table 23.

In the exploration phase, evaporation ponds can be considered as the best treatment option for disposing small quantities of wastewater. However, the environmental score for this treatment is low. Many vertebrates (including migratory birds) are attracted to evaporation ponds due to the abundance of food debris present in the wastewater and provision of sanctuary due to the adjacent large open spaces. Incorporation of transportation costs results in evaporation ponds being an expensive option compared to thermal and membrane processes.

The main environmental concern that is associated with all RO processes is the energy intensity. Energy as either electricity or steam produced using non-renewable sources of energy creates greenhouse gas emissions.

Table 23. **Evaluation output from the MCDA framework with option 4 being the most favourable and option 1 being the least favourable.**

Options		Equal Scenairo	Environment Scenario	Economic Scenario	Technology Scenario
Pond-Based	Solar Evap Pond - Clay	3	1	2	4
Pond-Based	Solar Evap Pond - HDPE	2	1	1	4
Pond-Based	Solar Evap Pond - Enhanced	2	1	1	4
Pond-Based	Concept Tank	2	1	1	4
Thermal Process	Brine Concentrator	2	3	2	2
Thermal Process	Forced Circulation Crystalliser	2	3	1	2
Thermal Process	Submerged Combustion (waste gas)	3	3	2	4
Thermal Process	Submerged Combustion (no waste gas)	3	3	2	4
Thermal Process	Small-Scale Forced Circulation Crystalliser	2	2	1	2
Membrane process	Standard Recovery RO	3	3	4	2
Membrane process	High Recovery RO	3	3	4	2
Membrane process	Very High Recovery RO	2	3	4	1
Novel/Hybrid Process	Humidification dehumidification	2	2	3	2

Ranking
1
2
3
4

Expensive, low-recovery treatments that generate additional, more concentrated waste streams do little to prevent the need for off-site transportation and in most cases will struggle to be economically viable. Moreover, from an environmental perspective, it cannot be asserted at this time that minimising the volume of disposed water at the cost of higher contaminant concentrations is an improvement over current practice.

7.12 Discussion

Each wastewater treatment system has environmental consequences that can have an effect on the ecosystem's efficiency, social health, and resource use. The variable quality of wastewater is a constraint on its reuse in irrigation, as it can influence soil salinity. Evaporation is a suitable method to reduce the volume of wastewater prior to offsite disposal. Evaporation ponds are a cost-effective option to be considered a viable solution for disposal of wastewater, especially in areas with high evaporation rates. However, there are operational limitations, including the overflow of wastewater, leakages via liners, and large surface area.

However, evaporation ponds are undoubtedly the most practical and efficient option for wastewater disposal in the Beetaloo region while the industry is still in exploration phase. The cost of transportation of waste is quite high and the evaporation option will not be viable for the industry in the production phase. MCDA framework demonstrates that thermal processes and RO processes, or some combination are frequently more attractive than evaporation processes as a desalination treatment for high-salinity produced water from shale gas fracturing.

Globally, membrane technology for wastewater treatment is driven by environmental regulations and the requirement to meet strict reuse standards for beneficial applications. Trends in membrane technology applications in the petroleum industry indicate that the need for membrane technology will continue to grow, as wastewater management practices have shifted their focus from discharge and re-injection to reducing, reusing, and recycling.

The Beetaloo Basin contains an estimated gas resource of 178,200 petajoules (PJ). The need for an economical and environmentally sustainable approach for managing the wastewater is critical, given the enormous volumes that are expected to be generated in the coming years in the Beetaloo region as the industry moves from exploration to the production phase.

8 Case studies

Shale gas and oil projects have a similar life cycle to other petroleum resources, consisting of exploration, appraisal, development, production, and site closure and rehabilitation (Figure 17). Exploration can take 3-5 years to identify the resource, followed by a 5-10 year appraisal phase to define the resource and make an investment decision to develop it. The development phase is a period of intense activity, where a significant amount of infrastructure is developed and a large number of wells are drilled and hydraulically fractured. The number of wells drilled depends on production rates, decline rates, and overall production targets. Once development is complete, the project enters the production phase, where oil and gas are brought to market. The duration of each phase can vary depending on the nature of the resource and external economic factors.

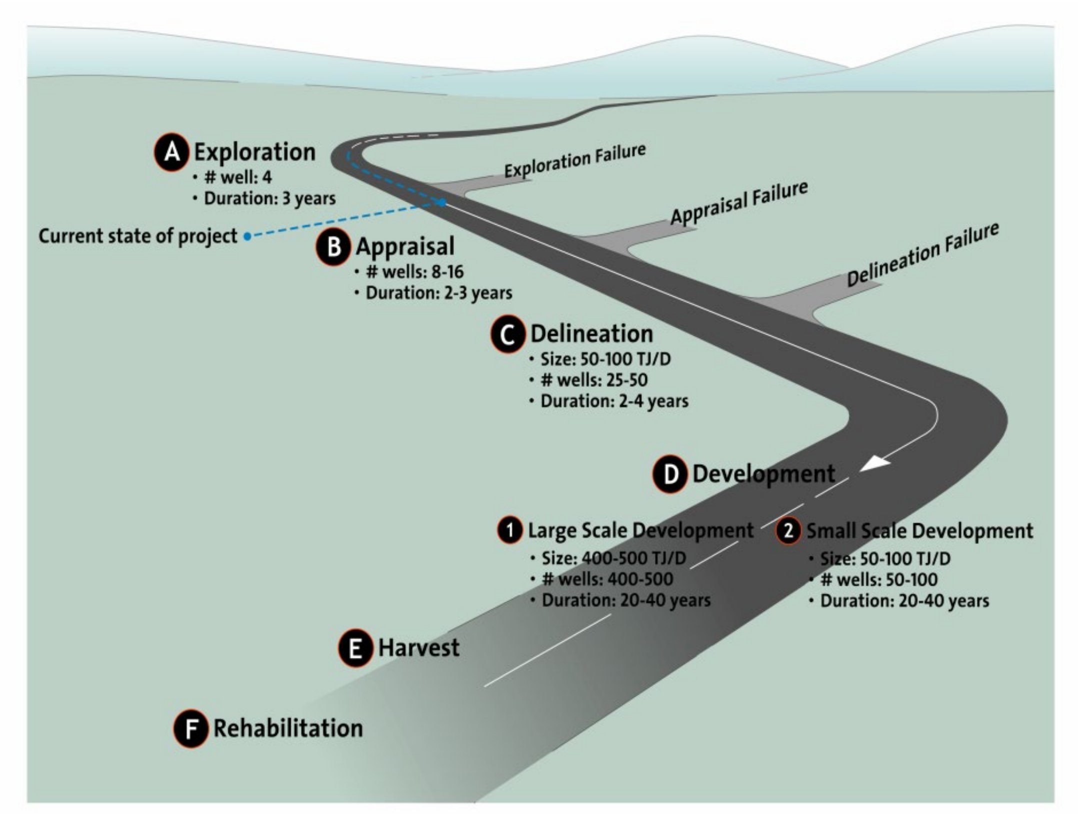


Figure 18. Conceptual Beetaloo Basin project pathway from exploration to development (Origin Energy, 2019b)

Since 2010, around 70 exploration and production wells have been drilled onshore in the Northern Territory (Government of Northern Territory, 2023). During 2022, Santos continued flow-testing at the Tanumbirini-2H and Tanumbirini-3H horizontal wells in EP161, which were drilled in 2021 to a total depth of 4598 m and 4857 m respectively. In September 2022, Tamboran Resources and Bryan Sheffield announced that they had agreed to jointly (50% each) acquire Origin Energy's 77.5% interest in three permits in the central part of the Beetaloo Sub-basin (EP 98, 117 and 76). Tamboran are now the largest acerage holder in the Beetaloo Sub-basin. In November, 2020, the Amungee 2H development well was drilled by Tamboran Resources and reached a total depth of 3883 m, including a 1275 m horizontal section. It was spudded on the same drill pad as the Amungee NW-1H, which was initially drilled and production tested in 2015-16, and is located 60 km east of Daly Waters. The well underwent fracture stimulation across 24 stages beginning in February 2023.

Following EMPs and flowback fluid monitoring results in the Beetaloo Sub-Basin were reviewed for the case studies:

- Amungee NW Delineation Program (Origin Energy, 2022)
- Amungee NW 1-H exploration well from 2015 to 2018 (DENR, 2019; Origin Energy, 2019a)
- Kyalla EP117 N2 (Origin Energy, 2021)
- Santos Tanumbirini 2H & 3H (Santos, 2022)
- Santos Tanumbirini_1 (Santos, 2020)

This information available was reviewed to:

- Compare the wastewater volume and quality generated at different sites during exploration phase
- Review pros and cons of offsite wastewater trucking
- Compare wastewater chemical concentrations against benchmarks to explore various reuse options considering realistic site-specific data
- Review beneficial reuse potential of treated water by other industries in NT
- Apply MCDA tool developed in this project to test the reuse readiness of each technology
- Propose a fit for purpose framework on the assumptions, and future projections such as well numbers, wastewater quality and quantity and disposal availability.

8.1 Water use in shale gas processes

During the exploration phase of shale gas development, water plays an important role in the process of hydraulic fracturing. The water cycle in this phase typically involves several steps and are outlined in Figure 18.

- Water sourcing: Water is sourced from nearby bodies of water, such as rivers, lakes, or groundwater wells, and transported to the well site.
- Water treatment: The water is treated to remove any impurities or contaminants that could potentially damage the well or reduce the effectiveness of the fracturing process.
- Hydraulic fracturing: The treated water is then mixed with proppants and chemicals and pumped into the well at high pressure to fracture the shale rock and release the gas.
- Flowback water: After the fracturing process is complete, the water that returns to the surface, known as flowback water, is collected and transported for disposal or treatment.

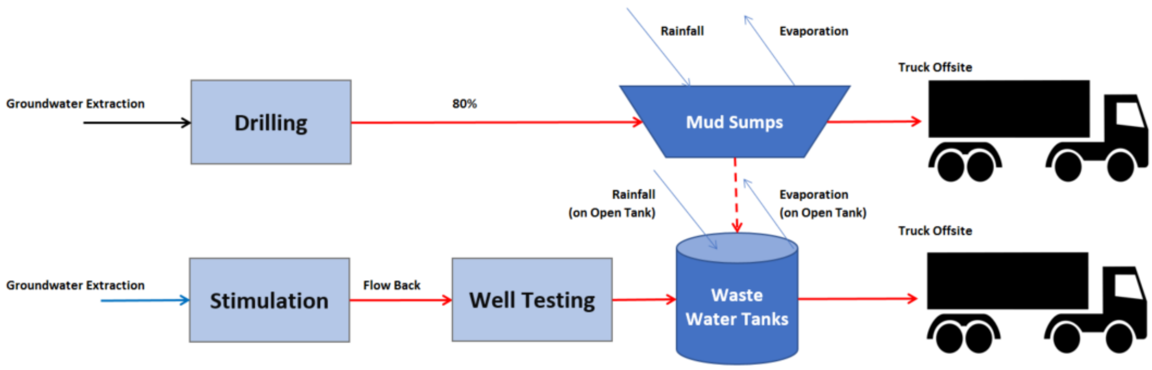


Figure 19. Water cycle in Exploration phase (Origin Energy, 2022)

The water usage in NT based on the exploration wells from four sites is listed in Table 24. Water use and flowback volume generation at well sites. The volume of water used in shale gas developments is approximately 5 to 20 megalitres (ML) per well. This variation results from several factors, including well length, formation geology, and fracturing fluid formulation. Industry estimates that 1,000-1,150 wells on 104-140 drilling pads in the Beetaloo are likely to use 2,500-5,000 ML of water per year (Pepper et al., 2018). No material change was detected in natural background values of groundwater quality attributable to well operations.

Table 24. Water use and flowback volume generation at well sites

Interest holder	Groundwater usage	Water used for stimulation	Flowback volume generated
ORIGIN ENERGY B2 PTY LTD (ORI11-3) 2022-2027	430 ML (107.5 ML per well pad (total))	25 ML per well (10-30 stages)	7.5 ML per well
Santos QNT Pty Ltd EP 161 2019-2024	85.2 ML (Tanumbirini 2H and Inacumba 1H wells each require 32 ML while Tanumbirini 1 requires 7 ML)	10-25 stages	10-20 ML/well for 25 stage process
Santos QNT Pty Ltd EP 161 2019-2020	85.2 ML (Tanumbirini 2H and Inacumba 1H wells each require 32 ML while Tanumbirini 1 requires 7 ML)	15-25 stages	5-20 ML/well

After hydraulic fracturing, a portion of the water returns to the surface as flowback, while the rest remains underground. The flowback water is typically stored in tanks or pits, and then transported to a centralized or decentralized treatment facility for treatment and disposal. Hydraulic fracturing (HF) occurred in the Tanumbirini_1 well in November 2019 in five stages at different depths in the target Velkerri shale formation more than 2,600 m below ground level (Santos, 2019b). During the flowback process that spanned over two months, a total volume of 3.2 ML was recovered, which accounts for approximately 40% of the volume that was injected into the impermeable shale during the HF operation. This recovery rate is consistent with the average rates observed in North American shale fields. Monitoring of flowback fluid volumes is given in Figure 19. No produced water has been encountered during flowback activities.

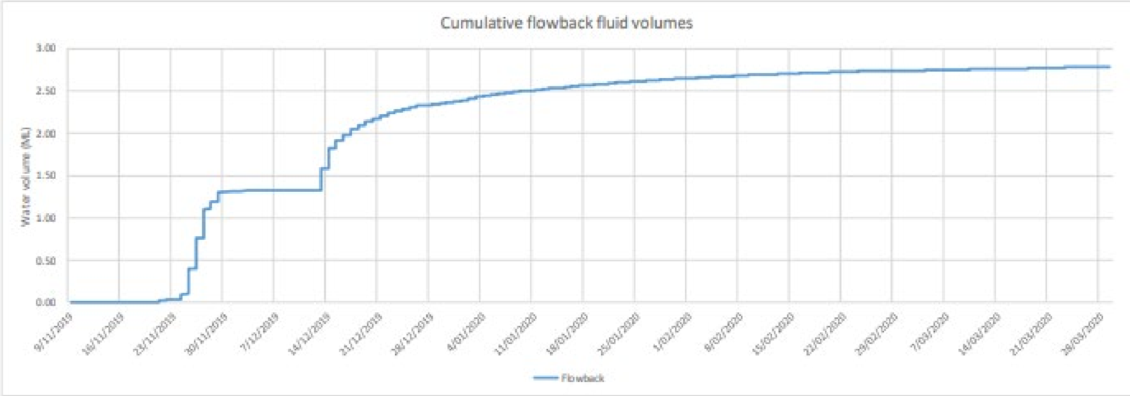


Figure 20. Recorded volume of cumulative flowback at Tanumbirini well site (from Santos Ltd, 2019b)

At Amungee NW 1-H petroleum well, total solids in the flowback was found to be comprised of approximately 93% sodium chloride, 5.3% calcium carbonate, 0.8% magnesium chloride, 0.25% barium sulphate, 0.2% potassium chloride and 0.12% boron, which accounts for 99.67% of the flowback constituents. Contaminants of potential concern in the flowback water, due to their persistence and higher toxicity in the environment including heavy metals (such as arsenic, cadmium, chromium and mercury), polyaromatic hydrocarbons (such as benzo[*a*]pyrene) were all below limits of reporting i.e. not detectable. Flowback water had approximately 80 times the level of chloride, 8 times the level of barium and 15 times the level of boron respectively of Gum Ridge aquifer values at the well site. The Amungee NW 1-H results are similar to those reported in major studies of flowback from shale plays in North America.

8.2 Wastewater management during exploration phase

The waste management hierarchy considerations are summarised in Table 25 and are based on Environment Management Plans submitted to NT government by Santos (2019a) for McArthur Basin Hydraulic Fracture Program. Other companies in exploration are also using evaporation methods to reduce the volume of wastewater and then truck it to the disposable site. The reuse options can only be evaluated once the industry moves into the production phase with more than 15 wells at a given site. Wastewater management considerations in the exploration phases for fracturing chemicals, drilling muds, drill cuttings and flowback water are listed in the Table below.

Table 25. Waste management hierarchy considerations from Environment Management Plans approved by NT government (Santos, 2019a)

	Avoid	Reduce	Reuse	Recycle	Treat	Dispose
Fracturing Chemicals	Cannot avoid	Recycling of fluids reduces the consumption of chemicals and therefore the production of waste	Chemicals returned to the supplier for future operations	Chemicals recycled	No treatment of chemicals is proposed	Disposed of in a licenced facility
Drilling fluids	Only water-based drilling mud used. Non-aqueous drilling mud not used.	Recycle fluids as much as possible	Transfer recycled fluids between wells where applicable Treat fluid to avoid bacteria and prolonged operational lifespan	Recycle fluids as much as feasible with available solids control equipment	Treat with drilling chemicals to facilitate recycling where feasible	Drilling fluids will be evaporated as much as possible; remaining fluid will be disposed of at a licenced facility
Drilling cuttings	Cannot avoid	Mud weights specifically designed for gauge wellbore, therefore minimise excess cuttings	Not proposed	Not proposed	Separate	Cuttings, burial or removal subject to sampling results, external environmental advisor and approval received from DPIR/DENR
Flowback fluids and produced water	Cannot avoid	Recycling of fluids reduces the consumption of additives, therefore, the production of waste	No re-use of fluids is proposed	No recycling of fluids is proposed	Maximise evaporation rates to reduce volumes	The remaining fluid will be assessed by a licensed waste management service provider It will be transferred to third-party process facility for further treatment and/or disposal in accordance with NT Waste Management and Pollution Control Act

8.2.1 Evaporation

Evaporation is the most common method used to reduce the volume of wastewater requiring offsite disposal. Wastewater treatment ponds and tanks are used onsite for this purpose. In compliance with the CoP, open tanks must be operated with a sufficient freeboard to not overflow with an annual exceedance probability for a 90-day rainfall event total that might be expected to occur once in 1,000 years for the period that treatment infrastructure contains wastewater. Mechanically enhanced evaporators are often used within the evaporation tanks to maximise evaporation rates and minimise associated storage and transport costs.

In a 13-month period (Origin Energy, 2021), at Kyalla 117 N2 with flowback from the Kyalla shale showed 84% reduction in wastewater volume, (~16,000 L/day). It is worth noting that this reduction was achieved with an electrical conductivity (EC) approximately 5-6 times higher than what is expected from the Velkerri shales. Velkerri shales will have an EC less than 50,000 µs/cm, which is significantly lower than the Kyalla shales that have an EC greater than 250,000 µs/cm. From the observations made at Kyalla, it seems that when the salinity levels reach saturation point, which is around 300,000 mg/L, bulk salt crystallization takes place and the salt begins to precipitate out of the solution. This process appears to facilitate the continuation of evaporation.

According to the latest EMP (Origin Energy, 2022), the main wastewater treatment method expected to be used is mechanical evaporators for enhanced evaporation in the four well pads with 12 wells in total. It is estimated that the use of enhanced evaporation will reduce the residual flowback volumes on each site from a peak of about 9.5 ML to around 0.5 ML within a year of well testing commencement (93%). After this, about 20 B-Triples will transport the remaining flowback to an approved disposal location. It is expected that the residual solids, brines, sludges, and liners will be sent to the Westrex waste facility in Jackson, Queensland as the default location, while other authorised facilities are being considered as alternative options. If such facilities become available during the disposal of flowback materials, they may also be used.

In addition, flowback will be preferentially used as stimulation make-up water where practicable. Before being injected downhole, flowback, raw groundwater, and stimulation chemicals will be combined in onsite mixers. This mixture is expected to make up roughly 30% of the stimulation fluid volume, which has the potential to significantly decrease the amount of flowback that needs to be stored and disposed of salinity and scaling constraint posed by wastewater restricted the use of conventional water treatment. It is not economically viable to set-up treatment technology to treat 10 ML/year for beneficial reuse.

8.2.2 Offsite wastewater transportation and its limitations

We conducted an industry survey to evaluate the costs involved in off-site transportation and treatment. The majority of responses confirmed off-site transport cost to be over $0.60/L of wastewater. Based on personal communication it was confirmed that 0.5 ML wastewater will incur disposal cost of $90,000 ($0.18/L) and the transportation costs would be close to $161,000 ($0.33/L). Such high costs to transport wastewater will not be feasible when the industry moves from the exploration phase into the production phase. In the Beetaloo Basin or any other region, trucking wastewater for disposal may not be a viable option if the cost of transportation is too high, suitable disposal sites are not available, regulations are too restrictive, or community concerns are not adequately addressed. In these cases, other disposal options, such as on-site treatment and reuse or deep well injection, may be more viable alternatives. Current relevant NT regulations and policies define how shale wastewaters be treated and contained, but do not present options for managing water used in shale gas operations.

According to Karapataki (2012) transporting water by truck can cost between $85 to $175 per hour per truck. It has been estimated by Gay and Slaughter (2014) that treating flowback for on-site reuse can result in cost savings of over $150,000 per well, which can lead to a 38% reduction in transportation costs. These cost savings resulting from reducing freshwater and wastewater transportation serve as a significant incentive for Marcellus play operators to maximize the reuse of wastewater. Moreover, heavy truck traffic often results in road damage for which Marcellus operators are held responsible and must maintain. Reducing truck trips will help reduce this expense, as noted by Yang et al. (2014).

According to Korfmacher et al. (2015), on-site recycling can decrease the total number of truck trips by 20%, which would result in lower costs for operators, as well as a reduction in emissions and other negative environmental, health, and economic effects associated with truck transportation. The use of trucks for transportation not only poses risks such as spills but can also result in environmental harm due to the emission of carbon dioxide, nitrogen oxides (NOx), sulphur dioxide (SO_2), and particulate matter. Additionally, it can contribute to congestion and accidents. Furthermore, accidents involving waste transport trucks can result in wastewater spills, the extent of which is dependent on local factors.

8.2.3 Assessment of reuse options based on the wastewater quality data

Part C of the Code of Practice (Government of Northern Territory, 2019) provides a framework for the management of water used in, and produced by, petroleum activities including storage, handling, transport, re-use, recycling, treatment, and disposal of wastewater. Analytes and method for drilling waste assessment are listed in Table 11 and C8 of CoP (Government of Northern Territory, 2019), providing a full suite of analytes to be measured in wastewater, including physicochemical parameters, nutrients, cations, anions, metals and metalloids, total recoverable hydrocarbons, polycyclic aromatic hydrocarbons, phenols, organic carbon and radionuclides.

Table 26 lists the key water quality parameters from five different operations in the Beetaloo region. The wastewater quality is highly variable with electrical conductivity from 15,000-200,000 µS/cm. The flowback waters and pond water are dominated by sodium and chloride ions, with high concentration of dissolved organic matter, which was a combination of geogenic and HF fluid-derived carbon. Chemical concentrations in the flowback waters were dynamic and changing. Boron, chromium, ammonia, zinc, manganese, ^{228}Ra, lead, ^{226}Ra, cobalt, cadmium, copper, aluminium, and nickel were above the Australian and New Zealand surface water quality default guideline values (DGVs) (ANZG, 2018; Apte et al., 2021) (Table 27). There are no aquatic ecosystem guidelines for boron and barium, but these are of concern based on the drinking water quality guidelines (Table 28).

Apte et al. (2021) compared the water quality data for the two wells to Australian and New Zealand surface water quality default guideline values (DGVs) (ANZG 2018). Twenty one contaminants exceeded these benchmarks in one or more of the samples collected. Hazard quotients were calculated for the final pond samples and indicated the following contaminants were of potential concern (hazard quotients in brackets): Tanumbirini-1: boron (46), chromium (41) and ammonia (24) and at Kyalla-117: zinc (209), manganese (86), 228Ra (44), lead (37), 226Ra (13), cobalt (11), boron (8), cadmium (4), copper (4), aluminium (3), and nickel (2). These contaminants plus the high salt and organic carbon content of the flowback waters are the main challenges for water treatment.

Table 26. Wastewater quality from five different operations (Apte et al., 2021; Origin Energy, 2019a; 2021; Santos, 2020; 2022)

ANALYTE	Unit	1	2	3	4	5	Range
pH	pH unit	8.02	5.8	7.1	6.5	6	5.8- 8.02
Electrical conductivity	µS/cm	15,417	204,000	60,700	57,000	65,383	15,000-200,000
Total dissolved Solids	mg/L	9,588	290,000	45000	49,200	-	9000-290,000
Ammonia	mg/L	28.9	100	<0.01	-	48.4	0.01-100
Chloride	mg/L	5,120	110,000	17,900	25,400	29433	5000-110,000
Sodium	mg/L	3,430	33,000	6620	13,900	12640	3000-14,000
Potassium	mg/L	36	900	10800	83	-	35-10,800
Magnesium	mg/L	66	3800	189	306	-	60-4000
Sulphate	mg/L	14	28	529	10	51	10-550
Calcium	mg/L	120	17000	178	1740	34845	10-35,000
Bromide	mg/L	61	910	22.9	-		50-1000
Boron	mg/L	16	3.3	0.10	45.4	4	50
Strontium	mg/L	3	530	1.69	-	-	1-530
Barium	mg/L	5	2000	0.959	80.1	215	1-2000
Iron	mg/L	315	220	1.04	-	99	1-315
TPH (C6-C40)	ug/L	26	300	1820	-	2117	26-2000
Gross alpha	Bq/L	0.5	36.2	0.96	-	-	0.5-35
Gross beta	Bq/L	0.5	97	32.3	-	-	0.5-100

Table 27. Wastewater reuse criteria for ecosystem, drinking water and irrigation

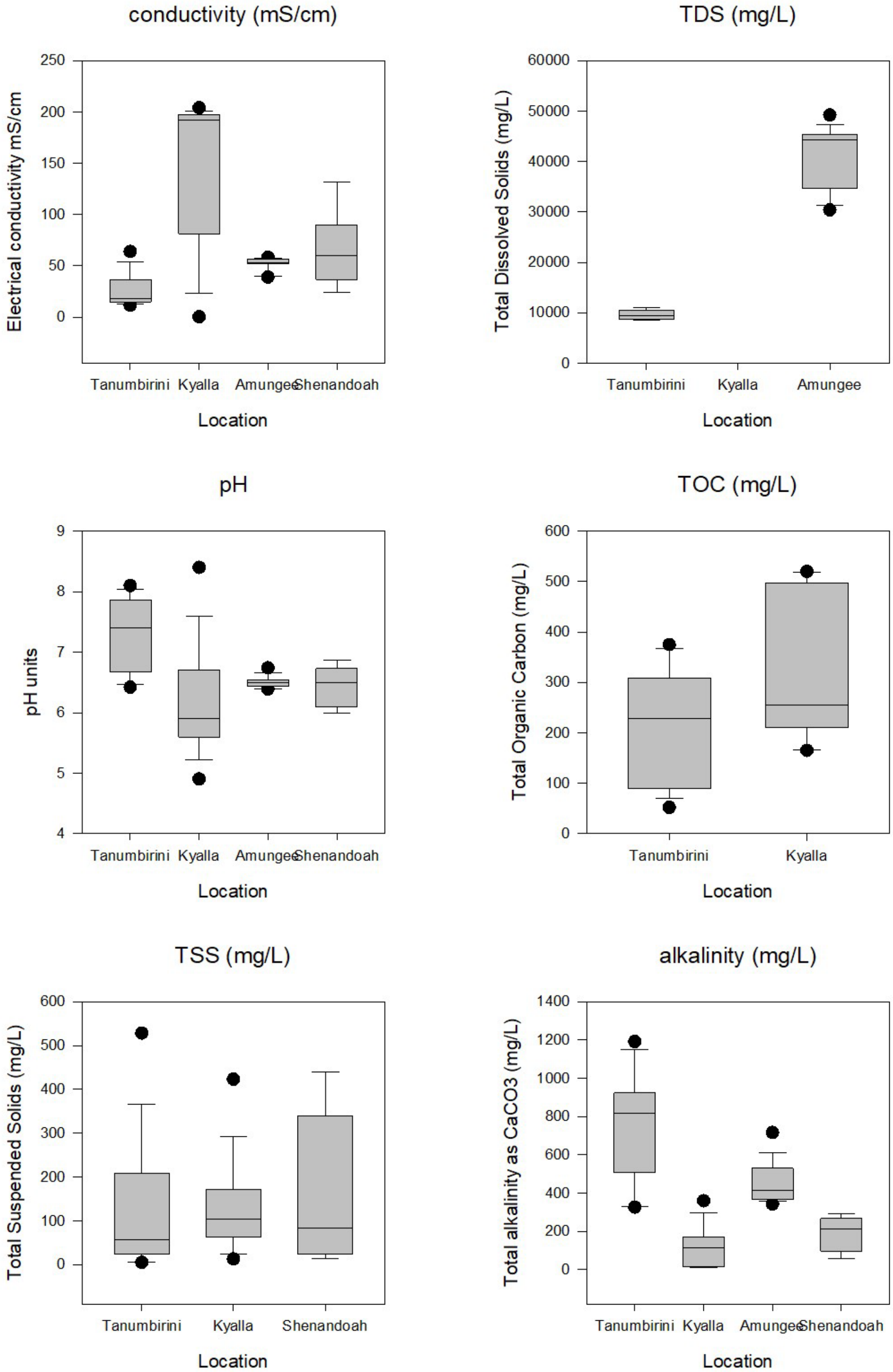
SETTING	Aquatic Ecosystems	Agricultural	
	Fresh Waters	**Irrigation**	**Livestock**
Electrical conductivity (dS/cm)	**0.5 – 1.5**	**1.3-2.9[a]** **2.9-5.2[b]** **5.2-8[c]** **>8[d]**	**up to 10[e]** **up to 4[f]**

[a] Moderately tolerant crops; [b] Tolerant crops; [c] Very tolerant crops; [d] Generally too saline for crops;
[e] Sheep tolerance limit; [f] Pigs and horses tolerance limit

Table 28. Guideline values for various end users

METALS/METALLOIDS					
	MarineWaters µg/L	Fresh Waters µg/L	Health Aesthetic mg/L	Irrigation (mg/L)	Livestock(mg/L)
Aluminium		<5 (if pH <6.5) <100 (if pH >6.5)	(0.2)	5.0	5.0
Arsenic (total)	50.0	50	0.007	0.1	0.5
Barium			0.7		
Beryllium		4		0.1	0.1
Boron			0.3	0.5-6.0	5.0
Cadmium	2.0	0.2-2.0	0.002	0.01	0.01
Chromium (Total)	50.0	10		1.0	
Chromium (VI)			0.05	0.1	1.0
Cobalt				0.05	1.0
Copper	5.0	2.0-5.0	2.0 (1.0)	0.2	0.5
Iron		1000	(0.3)	1.0	
Lead	5.0	1.0-5.0	0.01	0.2	0.1
Manganese			0.5 (0.1)	2.0	
Mercury (total)	0.1	0.1	0.001	0.002	0.002
Molybdenum			0.05	0.01	0.01
Nickel	15.0	15.0-150.0	0.02	0.02	1.0
Selenium	70.0	5.0	0.01	0.02	0.02
Silver	1.0	0.1	0.1		
Thallium	20.0	4.0			
Zinc	50.0	5.0-50.0	(3.0)	2.0	20.0

Livestock find water of high salinity unpalatable, but sheep raised in pens can tolerate up to 10 dS/cm. Horses and pigs have lower salinity limits (4dS/cm, Table 27). The high electrical conductivity of wastewaters (15-200 dS/cm) makes it unsuitable for irrigation and livestock drinking without prior treatment.


conductivity (mS/cm)
Electrical conductivity mS/cm
250
200
150
100
50
0
Tanumbirini
Kyalla
Amungee
Shenandoah
Location
TDS (mg/L)
Total Dissolved Solids (mg/L)
60000
50000
40000
30000
20000
10000
0
Tanumbirini
Kyalla
Amungee
Location
pH
pH units
9
8
7
6
5
4
Tanumbirini
Kyalla
Amungee
Shenandoah
Location
TOC (mg/L)
Total Organic Carbon (mg/L)
600
500
400
300
200
100
0
Tanumbirini
Kyalla
Location
TSS (mg/L)
Total Suspended Solids (mg/L)
600
500
400
300
200
100
0
Tanumbirini
Kyalla
Shenandoah
Location
alkalinity (mg/L)
Total alkalinity as CaCO3 (mg/L)
1400
1200
1000
800
600
400
200
0
Tanumbirini
Kyalla
Amungee
Shenandoah
Location

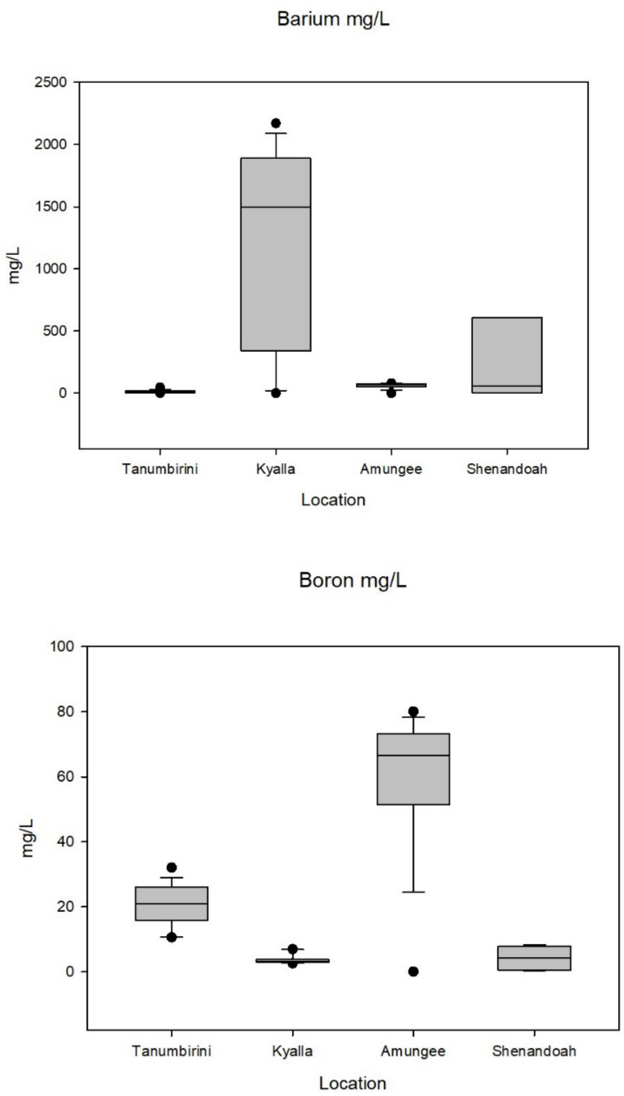


Figure 21. Box plots showing water quality monitoring results (Apte et al., 2021; Origin Energy, 2019a; 2021; Santos, 2020; 2022)

The Beetaloo Basin is in the early stages of exploration, so water quality data is scarce. This results in a high level of uncertainty in the variables that directly affect wastewater generation and availability, dependent on the geological properties of the shale formation and, to some extent, the design of the wells. If the temporal variability of flowback and produced water quality is not well understood, it can have a significant impact on the treatment and reuse of these waters. This is especially true when considering inorganic constituents that have the potential to cause mineral scaling in treatment processes (Oetjen et al., 2018). In addition, emerging contaminants such as PFAS and surfactants have not been analysed in the wastewaters testing conducted so far in Northern Territory.

The wastewater produced during exploration phase in the Beetaloo region has high salt content and is not fit for reuse. The wastewater is concentrated in evaporation ponds and trucked off-site. Based on the wastewater characteristics, the criterion Water Re-use Readiness has been incorporated into Treatment MCDA and the results are summarised in Table 29.

Table 29. Ranking the selected treatment options in terms of reuse readiness, with option 4 being the most favourable and option 1 being the least favourable

Treatment option		Reuse Readiness
Pond-based	Solar evaporation ponds - Standard clay lined	1
	Solar evaporation ponds - Standard HDPE lined	1
	Solar evaporation ponds - Enhanced evaporation	1
	Concept tank for evaporation	1
Thermal process	Brine concentrator	2
	Forced circulation crystalliser	2
	Submerged combustion (uses waste gas, i.e. free gas)	1
	Submerged combustion (no waste gas)	1
	Small-scale forced circulation crystalliser	2
Membrane process	Standard recovery RO	3
	High recovery RO	4
	Very high recovery RO	4
	Humidification dehumidification	2

Reuse readiness options	Ranking
None	1
Within treatment train	2
Irrigation/livestock drinking – moderate	3
Irrigation/livestock drinking – best	4

There is a need to understand the composition and time-evolution of flowback and produced waters in the different Australian shale locations where hydraulic fracturing takes place. The quantities and qualities of flowback water and produced water likely to be generated for shale gas development are dependent on local geologies and methods employed in extraction. Once these wastewaters have been characterised, it will be possible to identify approaches within a framework to guide industry and regulators to optimise the most appropriate approaches for re-use, recycling, treatment and disposal of wastewater based on ‘fit for purpose’ approach. Environment Management Plans (EMPs) for projects in the NT require wastewater management plans specific to single tenements or company developments; however, there is no industry-wide solution to address wastewater management at scale.

8.3 Potential reuse options of treated wastewater

The proposed uses of treated wastewater are diverse and can include irrigation, habitat watering, livestock supply, dust control, power generation and on-site operations.

8.3.1 Crop irrigation

The major water quality parameters for crop irrigation include salinity, sodium adsorption ratio (SAR), pH, alkalinity (carbonate and bicarbonate), and concentrations of specific ions (i.e. chloride, sulfate, boron, and nitrate-nitrogen (NO_3-N)). Other irrigation water constituents that may affect suitability for agricultural use include heavy metals and microbial contaminants Table 30 presents standards recommended for wastewater reuse.

Table 30. Standards recommended for reuse in irrigation, livestock consumption, and drinking purposes (Al-Ghouti et al., 2019)

Component	Irrigation (mg/L)	Livestock (mg/L)	Drinking (mg/L)
Li+	2500	-	-
Na+	Based on SAR	2000	200
NH3	-	-	1.5
Ca2+	Based on SAR	-	-
Mg2+	Based on SAR	2000	-
Cl–	-	1500	250
SO42–	-	1500	500
TDS	2000	5000	500
SAR	0-6	-	-

Depending on the quality of treated wastewater, it can be used on crops with different levels of salt sensitivity, as shown in Table 31.

Table 31. Soil and water salinity criteria based on plant tolerance groups (ANZECC & ARMCANZ, 2000)

Plant salt tolerance Group	Water or soil salinity rating	Mean root zone salinity (EC, dS/m)[a]
Sensitive crops	Very low	< 0.95
Moderately sensitive crops	Low	0.95 – 1.9
Moderately tolerant crops	Medium	1.9 – 4.5
Tolerant crops	High	4.5 – 7.7
Very tolerant crops	Very high	7.7 – 12.2
Generally too saline	Extreme	> 12.2

[a]1 dS/m = 1000 µS/cm

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

- 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 shall not exceed 3,000 µs/cm
- The maximum sodium adsorption ratio shall not exceed 8
- The maximum bicarbonate ion concentration shall not exceed 100 mg/L
- The maximum fluoride concentration shall not exceed 1 mg/L
- Irrigation techniques shall only include drip, centre pivot or lateral move irrigation machines fitted with low energy precision application systems
- Flood or related surface irrigation is specifically excluded
- The annual water application rate shall not exceed the water deficit (calculated on a daily basis)
- Deep drainage, due to irrigation, shall not exceed 15% of the rate of irrigation water applied to the surface
- Irrigation shall not be undertaken in circumstances where soil erosion is likely to occur
- Irrigation shall not be undertaken at a rate that results in water run-off to permanent water courses.

8.3.2 Livestock

When evaluating the suitability of produced water for livestock watering, a number of factors should be considered, including water quality, local conditions, availability of alternative supplies, seasonal changes, and age and health conditions of the animals. The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC & ARMCANZ, 2000) provide for recommended concentrations of TDS for livestock, as set out in Table 32.

Table 32. Tolerances of livestock to TDS in drinking water (ANZECC & ARMCANZ, 2000)

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

Pigs	0-4000	4000-6000	6000-8000
Poultry	0-2000	2000-3000	3000-40000

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

8.3.3 Dust suppression

Some oil and gas regulatory agencies in the USA allow operators to spray produced water on dirt roads to control dust. Similarly, the Queensland Department of Environment and Heritage Protection has identified dust suppression as a beneficial reuse application for produced water (Queensland Government Department of Environment and Heritage Protection, 2013). Generally, this practice is controlled so that wastewater is not applied beyond the road boundaries or within buffer zones around stream crossings and near buildings. Environmental concerns associated with dust mitigation using produced water include salt build up along roadways; migration of water and associated pollutants from the roadway; impacts to vegetation; and salt loading to river systems. In many cases, the risk of damage to soils or the ecology of flow paths leading away from roads on CSG tenures is likely to preclude application of produced water without some form of treatment (Queensland Government Department of Environment and Heritage Protection, 2013). In addition to salt-related concerns, impacts of other pollutants in wastewater must be considered. These include hydrocarbons, heavy metals and chemical additives used during drilling, stimulation, or workover of the wells.

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

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

A similar approach can be considered as a reuse option for shale gas WW in the Beetaloo region.

8.3.4 Internal reuse

In multi-well pad operations overseas, there is a growing practice to re-use flowback and produced waters in subsequent hydraulic fracturing operations in what is known as ‘internal reuse’ (Pepper et al., 2018). The internal reuse minimises the wastewater environmental impact and treatment costs while reducing the need for fresh water as fracturing fluid. However, the accumulation of high concentrations of dissolved solids can lead to operational problems.

Wastewater reinjection can also be explored after full scientific investigations determine that all risks associated with these practices can be mitigated.

8.3.5 Off-site industrial use

Off-site industrial use involving industries such as mining can present attractive beneficial reuse opportunities in some circumstances. A key requirement for financial viability is, in most cases, an industry with a large, relatively continuous and reliable water demand at a single or small number of locations. Given the water production profile of wells, a continuous level of supply may not always be achievable, and some storage capacity may be required to buffer production. Furthermore, the relatively short supply period of wastewater wells may not provide a strong incentive for major investment in water transport infrastructure. This may be an option worth exploring for the production phase when greater volumes are likely to improve cost effectiveness of this option.

8.4 Beneficial reuse potential of treated water by other industries in NT

The opportunity for beneficial reuse of treated wastewaters is largely dependent on:

- the potential industries and end users in economic distance from the source
- the available water volume and input water quality

Wastewater treatment methods in the Beetaloo for exploration and appraisal phases require transport of wastewater effluent approximately 2,500 km into Queensland, with the inherent safety, economic and environmental risks of long-distance transport.

A summary of current and potential future industries in the region therefore critically informs the analysis of plausible reuse options. Some of the most prospective reuse potential for large quantities of treated wastewater are anticipated to exist within the agriculture and mining sectors.

8.4.1 Regional land use and significant industries

The Beetaloo sub-basin area lies 500 km south of Darwin (Figure 21) on the Sturt Plateau, and is bounded by the townships of Mataranka (population 310) to the north-west, and extending to Elliott (pop 339) in the south (BRC, 2021; Huddlestone-Holmes et al., 2021; RGRC, 2021). The smaller settlements of Jilkminggan (pop 301), Newcastle Waters (64), Larrimah (47) and Daly Waters (9) are sparsely located across the region (RDANT, 2021).

Significant towns directly neighbouring the region include the regional service centre of Katherine (population 10,000) approximately 100 km from the northern boundary, and the Borroloola township to the east (population 870). The region is predominantly governed under the Roper Gulf Local Government Area (LGA) (Figure 22), crossing smaller components of the northern Barkly tablelands governed under the Barkly LGA (BRC, 2021; Huddlestone-Holmes et al., 2020).

Climate is predominantly wet-dry tropical, with absent to limited rainfall from May to September, and October to April characterised by a steep rainfall gradient (north to south) of high rainfall to the north (905 mm/year average) and arid to semi-arid conditions (567 mm/year average) to the south (CSIRO, 2009; Huddlestone-Holmes et al., 2020). Inter-annual rainfall variability is high and maximum annual rainfall fluctuates from three to seven times minimum annual rainfall (Huddlestone-Holmes et al., 2020).

Land use in the Beetaloo sub-basin is beef cattle grazing on dryland native vegetation, with no pasture improvement (Huddlestone-Holmes et al., 2020). This is indicative of the broader NT outback regional cattle industry, of which 45 per cent is cattle grazing on native vegetation (ABARES, 2016). Land ownership is comprised of Aboriginal land, perpetual pastoral leases (90%), horticultural enterprise and remote Aboriginal communities.

Industries are predominantly pastoral, horticultural, mining and, to a lesser extent, tourism. The largest employer by number of employed is the mining industry, closely followed by the government-dominated health, social assistance, public administration and safety sectors (Table 33).

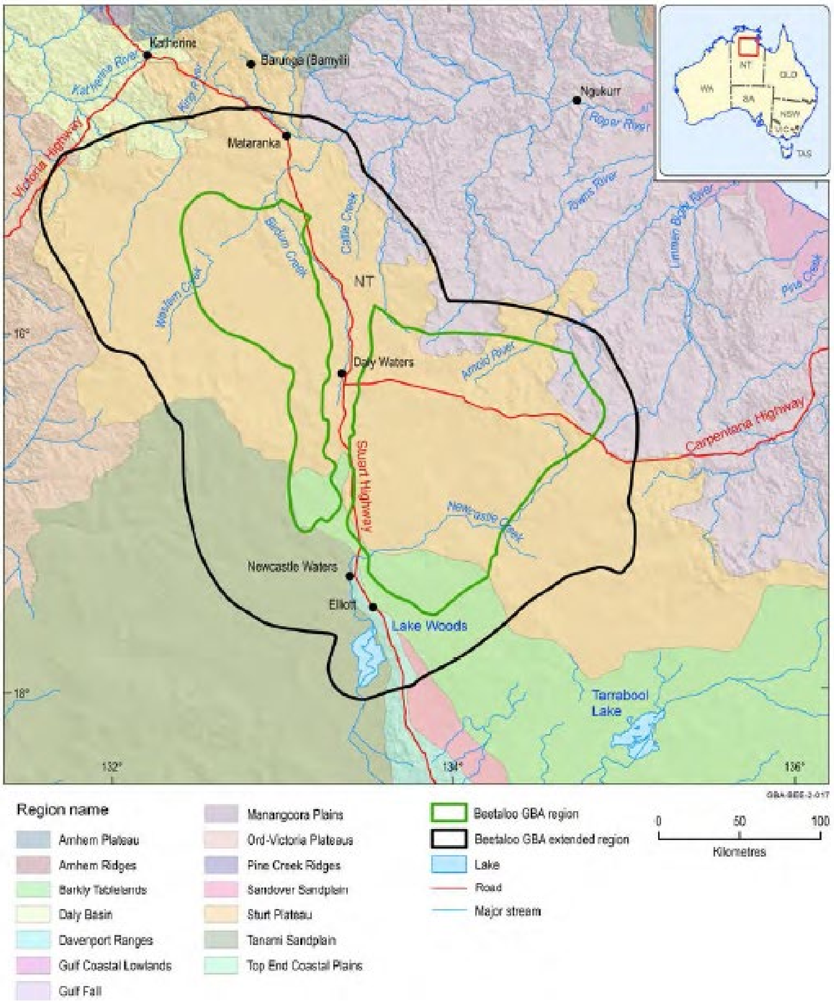


Figure 22. Beetaloo regional extent, as defined in the Australian Government's Geological Bioregional Assessment Program (Huddlestone-Holmes et al., 2020)

Figure 23. Roper Gulf Shire towns and administrative wards

Table 33. Major industries in the Beetaloo sub-basin (RDANT, 2021)

LGA	Largest employer by Industry	Next 5 major industries by employment (noting mining)	Total employed all industries
Roper Gulf	**Mining 20.3%** (All NT 5.4%)	Public administration and safety (16.8%) Education and training (11.4%) Health care and social assistance (11.2%) Other services (10.6%) **Agriculture,** forestry and fishing (7.9%)	2,522 (All NT 117,434)
Katherine	Public administration and safety (22.9%) (All NT 16.7%)	Health care and social assistance (19.4%) Education and training (9.3%) **Agriculture,** forestry and fishing (5.4%), Tourism (accommodation and food services, 5.7%) … **Mining (0.6%)**	5,132
Barkly	Public administration and safety (All NT 22.7%)	Health care and social assistance (17.3%) Education and training (12.9%) **Agriculture,** forestry and fishing (11.0%), Tourism (accommodation and food services, 4.8%) …. **Mining (1.7%)**	2,812

8.4.2 Mining

The production value of the combined extractive mining industry was $4.4 billion in 2019-20, comprising almost 20% of GSP, and the largest contributor to the NT's own-source revenue (NTDITT, 2020; NTGS, 2021). Whilst disaggregated data for the Beetaloo was not available, of the six major and four minor operating mines in the NT (NTGS, 2021), more than half exist in, or within 500 km of, the Beetaloo sub-basin region (NTGS, 2021):

- Macarthur River zinc, lead and silver mine, 70 km south-west of Borroloola (exporting from Borroloola's nearby Bing Bong Port)
- Bootoo Creek manganese mine, 110 km north of Tennant Creek
- Roper Bar iron ore mine, 50 km inland from the Gulf of Carpentaria and approximately 760 km from Darwin (exporting from Borroloola)
- Sill80 ilmenite mine in the Roper region
- Mataranka quicklime mine and cement processing operation south-east of Katherine
- Linecrest Pty Ltd, also exporting iron ore from reprocessed stockpiles at the Frances Creek iron ore mine near Pine Creek (170 km south of Darwin)

Many of these industries use water for extraction, ore separation and, in some cases, further processing.

Macarthur River Mine is a zinc and lead open cut mine on the Carpentaria Highway, 60 km west of Borroloola. There has been mining, processing and exporting of ore for 25 years through the Bing Bong port near Borroloola. Significant quantities of water are used during the flotation phase in processing to separate the valuable zinc-lead fines from waste rock (Xstrata Zinc, 2011). Estimates of water usage for the mining operation were not available. The input water qualities required for the mine are also unknown, requiring further research. However, documents suggest that mine dewatering and stormwater management provide ample supply to meet requirements. Stormwater management is a significant challenge during the wet season. Further investigation is required to identify if there are any potential symbiotic uses for shale gas wastewaters, or potentially for future treatment services that may be required in the region, such as a centralised facility.

Sill80 ilmenite mine is located in the Roper River region, approximately 105 km east of Mataranka Township and 8 km south of the Roper Highway. The mine processed 37,000 tonnes in 2019-20 and is yet to reach the anticipated production estimates of 100,000-300,000 tonnes of ilmenite per year. The ilmenite is intended for export to international markets for use in furnace linings in the steel industry and, with further processing, for products including paints, printing inks, fabrics and plastics (Murray, 2010).

Ilmenite production requires only water for separation, relying on the specific gravity of the different elements in the process (Murray, 2010). Sill80 was estimated to have a water use requirement of 1.5-3 ML per day or 300-1100 ML per year, sourced from the Roper River via a purpose built 12 km pipeline (Murray, 2010). At the Sill80 project inception, water limitations were identified as a problem for production, given wet and dry season fluctuations in the Roper River, and that processing would need to cease during periods of restricted flow and raw ore to be stockpiled. Local storage tanks needed to be included in the infrastructure design to allow some storage to meet demand at low flow times, which were estimated to be 5% of the year. However, based on Notice of Intent estimates at the moderate production scenario, tank reserves would be used from a few days to less than a day at the higher production estimate, and as such water limitations would require that the mine cease operations at low flows to avoid competing with adjacent communities for essential water supplies, and until flow returns to the river. Water was also intended to be recovered/recycled from ore processing adjacent to the mine site. However, likely yield estimates were not included at the Notice of Intent phase and it is unclear to what extent this would remove the production limitations. With these production restrictions and an already stated openness to use of recycled water, further investigation is required to identify if this could be another candidate for further use of recycled onshore gas wastewaters.

Northern Cement operates a quicklime mine and processing plant near Mataranka (also in Darwin and Alice Springs), with a predominantly dry mining processing operation. Total annual output in 2019-20 (across all three plants; disaggregated data not available) of around 23,000 tonnes (worth $6.6 million/year). Northern Cement also supplies bulk mixed cement to the mining, construction and transport sectors. Concrete has very specific input water quality requirements in Australian standards to achieve strength, safety and durability . Further research is required to understand the potential for reuse of onshore gas wastewaters for concrete batching for use in construction.

There are a number of substantial critical minerals projects in the region. There is potential for near-term production of lithium in the Pine Creek minerals province, and defined resources of copper identified around Borroloola (NTGS, 2021). Further analysis will be conducted on initial volumes and basic water usage requirements. However, a pre-feasibility study would be required to identify specific requirements of each mine to determine if there could be potential for an industrial ecosystem to be created with key customers for the reuse of shale gas wastewaters at scale across the region.

8.4.3 Agriculture

In recent years, the gross annual value of agricultural production in Northern Territory was $650-750 million, comprising 2.5% of GSP and employing 1.8% of the NT workforce (ABARES, 2020; NTDTF, 2021). The agriculture, forestry and fishing industries are a significant employer and economic driver in regional and remote areas and used by NT Treasury as an indicator of economic activity of the regions (NTDTF, 2021). Agriculture in the Beetaloo region is predominantly horticulture, mixed farming and cattle grazing (Figure 23).

The NT Government has identified Katherine for development of a logistics and agribusiness hub, given its importance as a regional centre for the surrounding cattle and horticulture industries and as a transport intersection between major road and rail networks (NTDITT, 2020).

Horticulture in the region is predominantly mangoes and melons, and smaller amounts of a range of fruits and vegetables. Broadacre cropping is limited to hay production. There is potential for expansion of field crops as part of dryland or irrigated production systems. Anticipated future crops include cassava, poppies, chia, lucerne, peanuts, cotton and soybeans (NTDITT, 2020).

The NT Government has identified the ‘Big Rivers’ region (encompassing the wider Darwin-Katherine region) as prospective for future agricultural expansion. Indeed, catchments around

Darwin (Finnis, Adelaide, Wildman and Mary Rivers) and the Roper and Victoria Rivers are the subject of land, water and agricultural potential studies to map the size and scale of the development potential (CSIRO, 2018). For cropping lands, 400 GL would be sufficient to trickle irrigate 50,000 ha of vegetables (CSIRO, 2018).

Whether treatment methods can deliver water qualities for beneficial reuse economically, safely, and to community acceptance will be a significant challenge for the industry. However, it is clear that potential water users in mining and agriculture sectors exist within the region and potentially further north in Darwin.

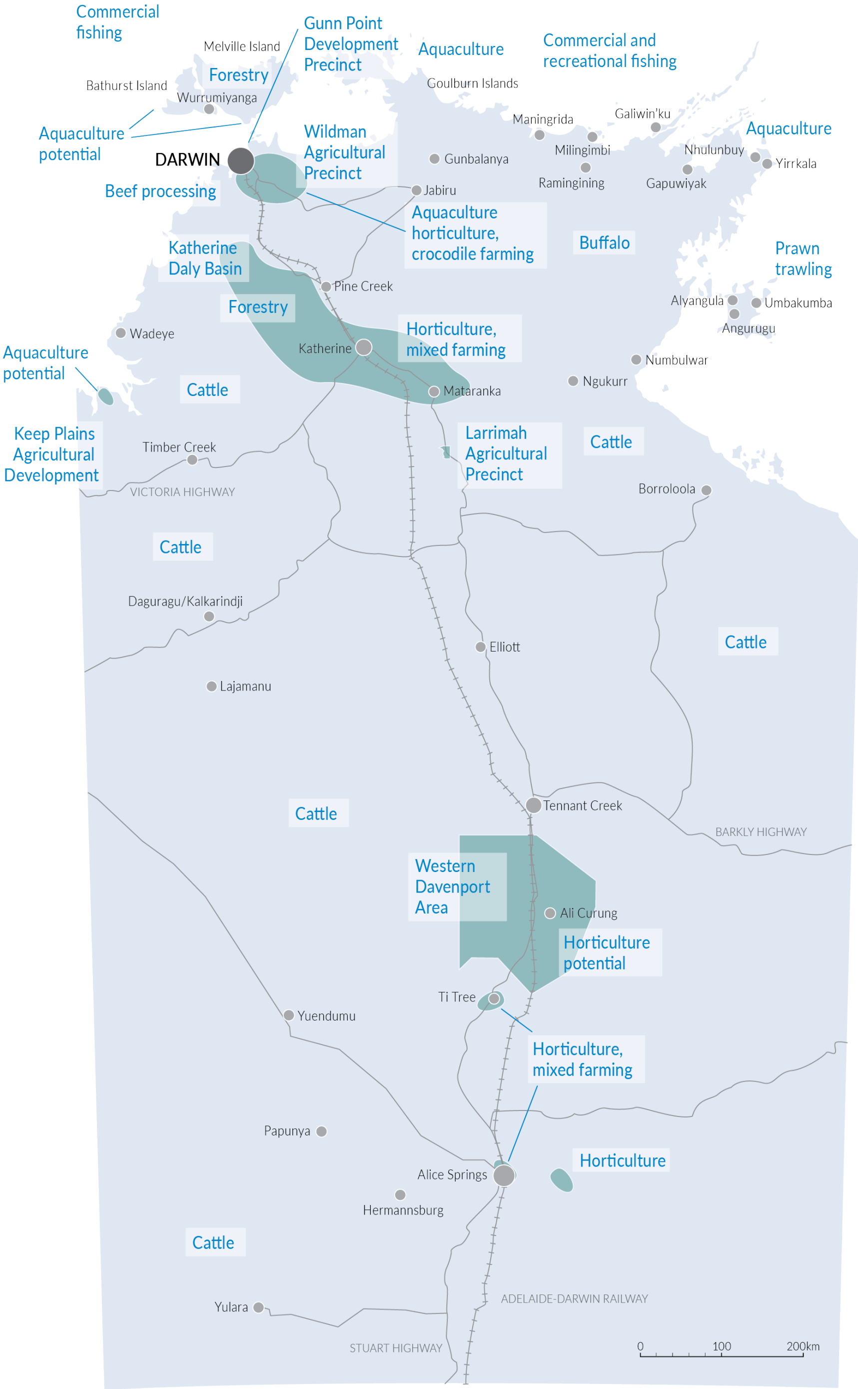


Figure 24. Northern Territory agriculture, farming and fisheries industry distribution (NTDTF, 2021).

8.5 Discussion

Managing increasing quantities of high-salinity wastewater containing contaminants such as hydrocarbons, sometimes NORM, and other organic and inorganic compounds within regulatory constraints will be a critical challenge as wastewater volumes threaten to overwhelm the limited infrastructure or become cost-prohibitive for transport and treatment interstate. There may also be insufficient wastewater users, such as agriculture irrigation and livestock, due to distance and remoteness. The gas industry may build treatment infrastructure that could be used and shared by other industries in the region. Further investigation of this option is required.

Industry estimates that 1,000-1,150 wells on 104-140 drilling pads in the Beetaloo are likely to use 2,500-5,000 ML of water annually (Pepper et al., 2018). While water reuse is an ongoing challenge for the shale gas industry, it is being explored and is likely to continue to be important in the Australian shale gas sector (Cook et al., 2013; Hawke, 2014; Pepper et al., 2018).

Beetaloo Basin project pathway from exploration to development predicts increase of production to 50-100 TJ/D (Table 34). Currently, RO technology is not appropriate due to very low volumes of wastewater being produced in the exploration and appraisal phases. As the industry moves into the production phase with higher wastewater production, it is expected to be economically more viable to use RO technologies for wastewater treatment. There is considerable potential for integrated membrane technologies to treat wastewater at its source in contrast to post facto segregation by type and subsequent membrane treatment in a central plant. Thus, the use of membrane technology in these potential applications may significantly reduce the cost and generate sufficient water for resource sustainability. Lewis (2013) provides an example for a well field capable of an annual production of 50 petajoules (PJ) of gas per year. In this example, approximately 90 wells are required in the first year and 50 wells in the second.

Table 34. Beetaloo Basin project pathway from exploration to development phase

Phases	Number of wells	Size	Duration
Exploration	4		3 years
Appraisal	8-16		2-3 years
Delineation	25-50	50-100 TJ/D	2-4 years
Development- small scale	50-100	50-100 TJ/D	20-40 years
Development – large scale	400-500	400-500 TJ/D	20-40 years

Centralised facilities that provide advanced treatment options like reverse osmosis, thermal distillation, or mechanical vapor recompression are capable of reducing TDS concentrations and effectively treating contaminants present in hydraulic fracturing wastewater. However, there is a lack of comprehensive data on the organic composition of such wastewater. Therefore, it is unclear whether advanced treatment methods are effective in removing constituents that are typically not included in standard testing protocols. If such contaminants cannot be removed by advanced treatment technologies, then the water will not be fit for crop irrigation.

A "fit for purpose" approach for wastewater management involves designing and implementing treatment processes that are appropriate for the specific type of wastewater being treated and the intended end use of the treated water. This approach takes into consideration the composition of the wastewater, the required treatment levels to meet regulatory standards or other quality targets, and the potential end uses of the treated water. For example, if the treated water is intended for irrigation purposes, the treatment process may need to focus on removing TDS , nutrients and other contaminants that could negatively impact crops or soil quality.

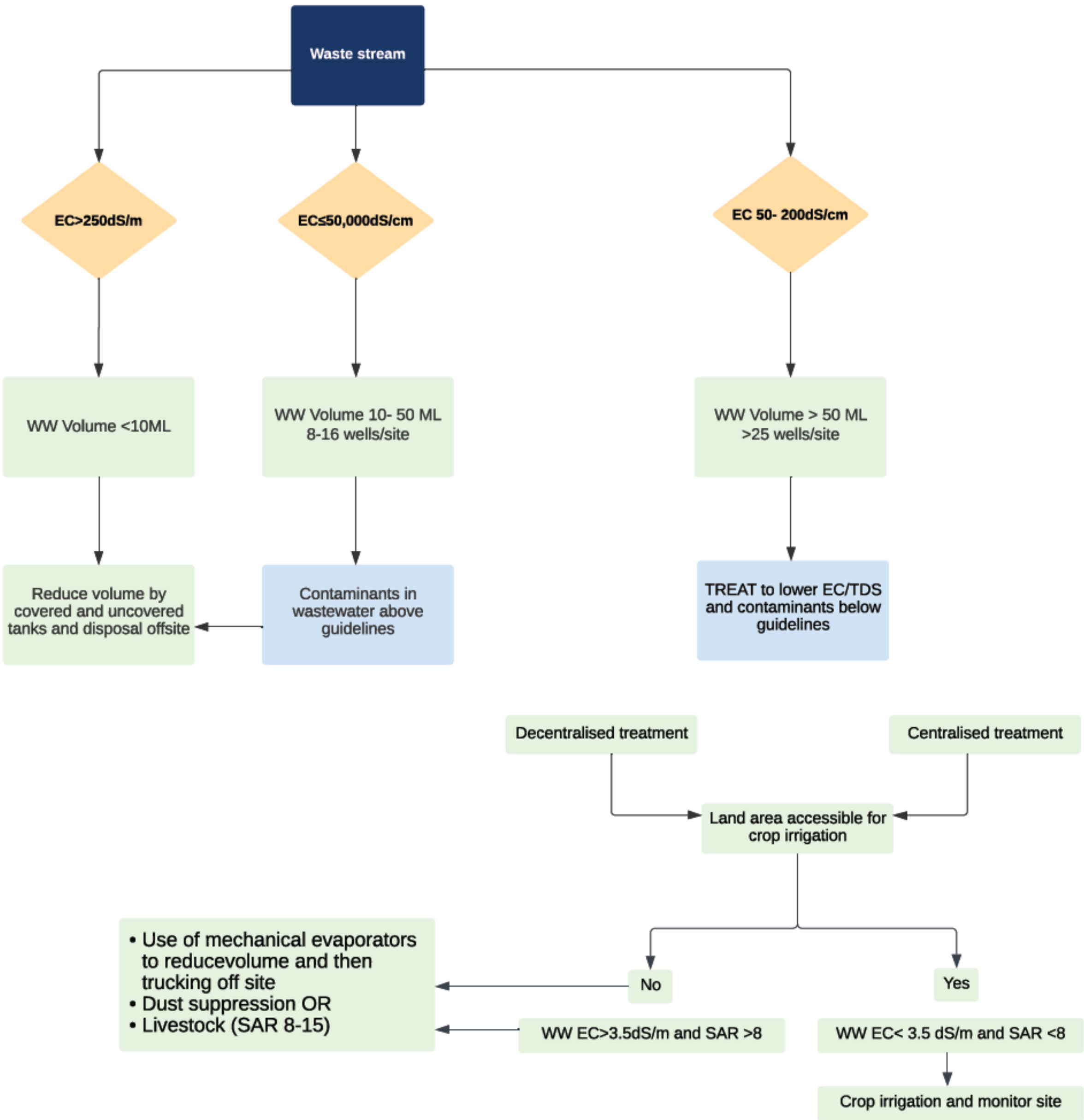
A fit for purpose approach for wastewater management has been outlined in Figure 24 to demonstrate various reuse options based on wastewater quality and volume to ensure that treated water is safe and suitable for its intended use, while minimising treatment costs and environmental impacts. The volume of wastewater is an important factor to consider when applying a fit-for-purpose approach for its reuse. Depending on the quality and quantity of the wastewater, it can be treated to various levels and used for different purposes.

High TDS levels in wastewater can impact the effectiveness of treatment processes and limit potential reuse options. All operators are in exploration and appraisal stages, concerning the proving up of the gas resource available to be exploited. At this stage they have an overarching need to avoid adding variables by using recycled water - for example, hypersaline water used for stimulation may impact the formation and reduce productivity (i.e., through ionic exchange, impacts to clays, formation clogging etc.). This could provide a false negative on the prospectively of the resource. Reuse trials are typically completed once production results from the formation are confirmed through detailed appraisal and most variables are known. Right now, only a handful of wells have been tested-therefore reuse opportunities during this phase are low. Reuse use trials are likely to begin once a) a resource is confirmed and reserves move from contingent to probable and b) once at least 10 wells per formation are drilled by an operator. Physical limitations to the installation of equipment, lack of storage capacity or conveyance pipelines, and compatibility with existing infrastructure may also hinder reuse options

A Visual Basic for Applications (VBA) integrated decision support tool (iDST) was developed by Geza et al. (2018) to select a combination of treatment technologies or treatment trains for different types of alternative water and beneficial use options, such as potable use, crop irrigation, livestock watering, hydraulic fracturing, well drilling, environmental restoration, and other industrial applications. There is the potential for similar tool to be developed for the shale gas industry in NT as industry develops, and more site-specific data becomes available. As industry moves from 2-3 wells to more than 50 wells at a given site. In their study, Gay and Slaughter (2014) analysed the impact of water management on the capital and operational expenditures of wells. They explored four different scenarios and estimated that water-management CapEx accounts for approximately 6% to 13% of the total well CapEx. Furthermore, water management represents a significant portion of the total annual OpEx for each well, ranging from 27% to 53%. To reduce these costs, the authors suggested that operators should consider recycling wastewater. Their analysis showed that even in cases where disposal costs are high, operators who recycle water could potentially achieve a 25% reduction in CapEx and an annual OpEx savings of 38%. This should be tested under Australian conditions based on the site-specific data.

No single technology is likely to result in the effluent requirements for discharge or re-use (outside direct hydraulic fracturing reuse). Costs of treatment are \$0.10 – 0.95/L depending on the TDS levels. Opex for various alternative treatment options are \$2-60/m^3 feed. More likely, a combination of pre-treatment techniques, evaporation ponds for disposal of highly saline wastewaters and new desalination technologies will have to be used to minimise the environmental impact of wastewaters from shale gas production by hydraulic fracturing

There are a range of potential mining, construction and agricultural uses for suitably treated reuse water in the Katherine and wider Beetaloo basin region. There is likely to be further potential for industrial reuse in Darwin associated with chemical industries.



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EC- Electrical conductivity, SAR- Sodium Adsorption Ratio.

Figure 25. Decision support framework for wastewater management based on the fit for purpose approach

9 Conclusions and recommendations

Flowback water contains a number of constituents, depending on the fracturing fluid and the shale formation and varies dramatically across shale plays. There are additives from the drilling and fracturing fluids (e.g. biocides, scaling inhibitors, friction reducers) as well as salts, organic compounds, sulfates and metals (e.g. calcium, magnesium, barium) present in the formation, and naturally occurring radioactive materials. Developing a program that produces wastewater that is fit for a particular disposal method will be an iterative process that involves disposal methods and the production process. Based on the information collated and analyses conducted in this project, the key points are summarised below.

The disposal systems currently in use include evaporation followed by trucking offsite. According to MCDA treatment module, evaporation ponds can be considered as the best treatment option for disposing small quantities of wastewater. However, the environmental score for this treatment is low. Trucking is often the most visible and socially objectionable aspect of shale gas production but also poses health risks, including spillage, emissions of particulate matter, and increased risk of motor vehicle accidents. Development of a treatment plant in the NT would provide valuable transport cost savings for companies otherwise needing to truck residual wastewater from fracturing to Queensland for treatment, reduce transport related health, safety and environmental risks and support employment growth. High-level analysis indicates that a NT treatment plant would offset significant transport costs, and may be able to charge commercially viable gate fees, as users would incur greater costs transporting the wastewater interstate.

The beneficial reuse of the fluid is not considered feasible during exploration phase. Based on the wastewater characteristics, the criterion Water Re-use Readiness was incorporated into Treatment MCDA module. MCDA model also confirmed evaporation ponds as the best treatment option for disposing small quantities of wastewater. However, the environmental score for this treatment was low.

Wastewater generation involves high salinity levels that increase with production time. Treating high-salinity wastewaters for beneficial reuse or discharge is costly and energy-intensive. In this report, cost estimates provided to an order of magnitude level of accuracy (pre-feasibility) and do not consider the scenario-specific complexities of individual projects, which require more detailed design and engineering to ascertain. Actual prices, costs and other variables may be different to those used to prepare the cost estimate and may change. Feasibility of decentralised and centralised options for the storage, re-cycling, or disposal in treatment option module can be further explored on a commercial or fee for service basis. This will further demonstrate the development of localised treatment options as the industry moves into the production phase. There is a strong potential to explore and evaluate local treatment options and cost implications and investigate potential for a combined solution serving multiple operators.

The wastewater volume generated is predicted to increase as the industry moves from exploration to production phase. The application of evaporation technology will not be viable as the production of wastewater is anticipated to be greater than 50 ML/site in the development and production phase. TDS is highly variable in wastewater and the cost per cubic metre for treatment of flowback fluid at Jackson facility is \$0.10 - \$0.95/L. The cost of off-site disposal would also increase due to higher transportation costs. Managing such large quantities of wastewater in the development phase is further complicated by its low quality. The high concentrations of dissolved salts and trace metals and naturally occurring radioactive species could present significant treatment challenges.

Integrated membrane technologies have considerable potential to treat wastewater at its source in contrast to post facto segregation by type and subsequent membrane treatment in a central plant. Thus, membrane technology may significantly reduce the cost and generate a sufficient amount of water for resource sustainability. This technology requires significant infrastructure and has associated costs and potential benefits. It would be prudent to modify the quality of the wastewater so that it is optimal for the chosen method of ultimate disposal and reuse.

Economic, social and geographic feasibility of treatment options must be decided upon, taking into account community opinion and cultural implications, the cost of on-site treatment set-up or transport to off-site treatment plants, and guideline requirements for contaminant levels in treated wastewater for reuse.

There is still uncertainty regarding the quality of HF flowback water in the Beetaloo. It varies spatially and is highly dependent on target formation. Once a field location moves to appraisal stage, stakeholders can determine the possible treatment/reuse as the ‘in-fill’ drilling program can expect a reasonably consistent quality of flowback once it has been characterised in earlier exploration stage for the target formation.

Monitoring of the environment will be required for most disposal systems, including evaporation basins, ‘treat and store’ and irrigate and rapid disposal. Codes of Practice describe the monitoring required. The monitoring data should be used to determine how the production, treatment and disposal processes should be modified to minimise environmental impact in an economically feasible manner.

No single technology is likely to result in the effluent requirements for discharge or re-use (outside direct hydraulic fracturing reuse). More likely, a combination of pre-treatment techniques, existing use of evaporation ponds for disposal of highly saline wastewaters and new desalination technologies will have to be optimised in order to minimise the environmental impact of wastewaters from shale gas production by hydraulic fracturing.

The variation in wastewater quality and treatment objectives implies that technologies must adopt a ‘fit-for-purpose’ philosophy to match the treated water quality to the intended use. The approach aims to avoid overtreatment and the legally prohibited under-treatment. Water quality depends on the level of feed water and wastewater treatment, which is in turn dictated by the end use of the water.

Based on the research, literature reviews and stakeholder consultation undertaken, the project makes the following recommendations:

1. Even assuming wastewater recycling rates in the region rise, meeting increased demands for wastewater treatment would require significant capital investment to expand disposal pathways, namely treatment and discharge at centralised facilities. This should be further explored.
2. Beneficial reuse in other industrial operations is limited due to lack of economic incentives and potential liability issues for operators. This should be jointly addressed by the government and industry stakeholders.
3. There is a need to re-evaluate regional-scale shale wastewater management practices, as strategic planning will result in more socially and economically favourable options while avoiding adverse environmental impacts that could overshadow the environmental benefits of natural gas expansion in the energy sector.
4. Injecting highly saline wastewater into rock formations risks inducing seismicity. This is one of the greatest potential barriers to expanding wastewater injection. This subject should be further investigated based on the reinjection technology being implemented in other countries.
5. Open communication with the public is essential to ensure transparency and appropriate engagement throughout the life cycle of shale development. Cultural values are included in the EMPS of all industries and should be maintained throughout the expansion of the industry.
6. Safe, cost-effective water storage is critical to the industry. Due to the unpredictable characteristics of wastewater, an ideal and optimum combination of different technologies must be developed to ensure adequate treatment.
7. The feasibility of decentralised and centralised options for the storage, re-cycling, or disposal in treatment option module can be further explored on a commercial or fee for service basis. This will further demonstrate the development of localised treatment options as the industry moves into the production phase. There is a potential to explore and evaluate local treatment options and cost implications and investigate potential for a combined solution serving multiple operators.

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