Office of the Queensland Mine Rehabilitation Commissioner

A review and comparison of approaches to treat coal mine affected water in Queensland

Student project report

Queensland Government

Prepared by: Office of the Queensland Mine Rehabilitation Commissioner

Disclaimer

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Foreword

This report is an output from a student project that was undertaken as part of a three month higher degree Industry Placement program. The review is not intended to provide a full representation of the scientific literature on the subject matter, but rather provide a platform for further research on water technologies for rehabilitation of coal mine void water. The water technologies reviewed in this report are not an exhaustive list of all treatment options. This project collated key literature and developed an approach to assess and broadly compare water treatment options for coal mines. This report does not seek to identify the best water treatment approach for the coal industry. However, this report describes a framework that can be used to identify, assess and compare water treatment options. The approach presented here could be further developed and applied on a site level to identify an appropriate water treatment option.

Contents

Figures

Tables

Executive Summary

Coal mining in Queensland occurs mostly in dry and inland regions. Where residual voids are left open after mining, they typically fill with water and the quality of water held in voids can decline over time due to ongoing contaminant input and high rates of evaporation. Water held in coal mine pits in the Fitzroy River Basin is often associated with elevated salinity and sulfate and a range of metals (e.g., aluminium, selenium, copper and zinc) may also be present. Although the quality of Coal Mine Affected Water (CMAW) can vary between mine pits, some level of treatment is typically required to meet standards for re-use. Water treatment can be undertaken to facilitate greater beneficial use and limit the waste of water as a precious resource. Ongoing treatment and re-use of mine affected water can reduce the volume of water and limit contaminant loads that remain in residual voids at the end of mining. Ongoing water treatment during and after mining can also limit mine closure risks and improve the options available for post-mining use of water held in mine voids. Despite the potential benefits, water treatment is not commonly undertaken in the Queensland coal industry at present. Accordingly, there is a need to better understand the opportunities and constraints for integrating water treatment into site water management and rehabilitation planning.

The overall objective of this study was to describe a framework to identify, assess and compare water treatment options for treating coal mine affected water from residual coal mine voids in Queensland. The aim is to be able to treat water to a standard sufficient to support beneficial use of water during and after mining and avoid the accumulation of dissolved salts and contaminants in mine affected water storages. Current literature on the key groups of water treatment technologies were reviewed and evaluated for their potential application in the Queensland coal mining industry. The typical salinity levels of current coal mine affected water and predictions of the expected salinity of post-mining void waters in Queensland were characterised. The options for treating coal mine affected water to a standard suitable for a range of beneficial uses were identified and a framework to compare them was defined. Water treatment technologies were assessed in terms of both their suitability and feasibility using a standard set of criteria. The criteria used to assess the suitability of treatment approaches included operational requirements such as the potential treatment rate, capacity to remove salt, the water recovery rate, need for maintenance and the technical skill and training required to implement them. The criteria used to assess the feasibility of treatment approaches included the costs related to pre-treatment, energy use, infrastructure requirements, waste management considerations, and requirements for beneficial uses or release. Treatment options were considered in the context of treatment of water held in saline mine voids that typically develop from coal mining in Queensland. Treatment of acidic metal-rich waters that typically develop from other types of mining were not considered here.

Existing water treatment technology such as membrane techniques provide an effective way to treat coal mine affected water to a standard suitable for beneficial use. However, such approaches require high energy inputs and can generate waste that requires disposal. New approaches are being developed to help overcome these shortcomings but will require further development and trials to demonstrate their effectiveness before they can be adopted more broadly.

Although there is no ideal treatment technology that will fit all cases, the suitability of water treatment techniques will depend on site-specific factors as well as ensuring the level of treatment undertaken matches the requirements for any beneficial use. The approach to assess and compare water treatment options described here provides a qualitative evaluation of the suitability and feasibility for treating saline mine affected water typical of Queensland coal mines.

Key findings from the review of water treatment techniques are as follows:

- Reverse osmosis (RO) is a widely used technology that is proven to be effective in removing salts. Although it is likely to provide the best treatment solution for highly saline coal mine affected water, it can be expensive due to high energy costs and the need for disposal of concentrated brine.
- Forward osmosis (FO) is an innovative pre-treatment for RO that provides a low-cost way to passively remove some salt before treatment with RO resulting in reduced energy input and treatment costs. Recent trials at a coal mine in NSW have demonstrated treatment of up to 10 m^3/day using FO.
- Electrodialysis (ED) uses electricity rather than high pressures to remove salt and recent advances have made it potentially more cost effective than RO. The alternative, reverse electrodialysis (RED) shows great potential to reduce the need for chemicals and can also potentially generate electricity. ED and RED have the potential to outperform RO in terms of

costs and pre-treatment requirements, but lack large-scale demonstration, and generate a brine waste stream, similar to RO.

- Research into the use of nanotechnology membranes have been reported to reduce treatment cost and increase salt removal for both RO and ED but require further research and development before they could be adopted at coal mine scale.
- Constructed wetlands (CWs) provide a relatively low-cost way to passively remove metals, nutrients and sulfate but are generally not well suited to remove salts. Accordingly, wetlands have greater potential for application in metal-rich systems rather than typical Queensland coal mine waters. The use of salt tolerant plants has some potential to improve the treatment efficiency but would require further research and testing.
- Biodesalination is a relatively new treatment technology that works through salt uptake by microorganisms and subsequent harvesting of biomass. Recent research shows the potential to remove salts via biodesalination at much lower cost, but further research is required before it can be used at a large scale.
- There are opportunities to reduce the cost of energy consumed during water treatment by utilising renewable energy or by applying low-cost innovative pre-treatment such as FO. Where water is treated to a high quality, it can be used for a range of beneficial purposes that may generate income providing an opportunity to further offset treatment costs.

1. Introduction

Residual voids are often left in place after open cut mining operations cease, and as many mines reach the end of their economic life, they are likely to become increasingly common in the future. Voids may be left in place for a range of reasons that can include the need to prevent offsite impacts or where it is not possible or feasible to backfill them. Such practices often form water filled residual voids (also called pit lakes in some jurisdictions), that in some cases can pose a threat to local fauna, flora, and the community.

Residual voids that extend below the water table fill with water after mining and dewatering operations cease. In central Queensland, the higher rates of evaporation compared to surface and groundwater inputs can result in a negative or neutral water balance where they act as ‘contaminant sinks’. Under such conditions, water quality is likely to deteriorate and become unsuitable for most beneficial uses in the long-term. Although less likely to occur in central Queensland, where there is no substantial water loss and excess water accumulates, residual voids can have a positive water balance requiring a reduction in water levels to ensure structures remain safe and stable.

Proactive management to remove contaminants can increase beneficial use and limit the potential for offsite impacts to surface and groundwater resources. The hot and dry climate in parts of Queensland combined with relatively few perennial water bodies in mining regions, make residual voids a potentially valuable water resource. If water held in residual voids is left untreated or they are poorly managed, it is likely they will become an ongoing liability. However, water treatment is not commonly applied in coal mining in Queensland. There are many constraints and barriers to adopting water treatment options such as technological requirements, costs, energy, waste, training and expertise.

This report aims to describe a framework to identify, assess and compare water treatment options for treating saline water from coal mine residual voids in Queensland to a standard sufficient to support beneficial use of water during mine rehabilitation and after closure. The specific objectives were to:

- Review the available scientific literature to identify and describe current and emerging saline water treatment techniques,
- Describe the typical salinity of current coal mine affected water and predicted residual voids from coal mining in Queensland,
- Define the level of water treatment required to achieve common beneficial uses from typical coal mine void water.
- Evaluate suitability and feasibility for implementing some established techniques for treating saline water generated from coal mining activities in Queensland.

This report provides a summary of available water treatment technologies and describes an approach to broadly compare water treatment options for pit water from coal mines in Queensland. It does not seek to identify a single ‘best’ water treatment approach for the coal industry. The report outlines the constraints that limit the sustainable use of technologies in water management strategies. There are a range of issues that can affect whether water treatment could be used successfully at a site level. The present report provides the foundation for developing operational guidance that would allow mine sites to proactively, rather than reactively, utilise water treatment to manage their water systems.

2. Water treatment across the mine life cycle

This section provides an understanding of water management in mining and describes how water treatment fits within the mine life cycle from operation to closure and post-closure. Water should be managed proactively throughout the entire mine life cycle, from exploration, feasibility, and construction phases to operation and processing stages until closure and long-term monitoring. Figure 1 displays a decision-making framework for water management in mining activities, highlighting the role treatment plays in managing and repurposing water across the life of mine including mine closure. In Figure 1, the legend within the figure shows the definition of acronyms. Green hexagons in the figure represent fundamental decision-making steps in managing water on a mine site. The decisions shown in the site water management process are related to the quality and quantity of available water and demand for use. The primary inputs of water are from external supplies and surface and groundwater intercepted on site. Water is held on site in mine affected water dams and in some cases mine voids are also used as storages. Water is used in mine operations for a range of purposes such as processing, dust suppression, wash down and human consumption. Excess water is stored or released via regulated discharge points. Water quality and quantity will determine the management strategy needed and the urgency of interventions. Integrating water treatment during the operational stages of mining can help to facilitate re-use of worked water, reduce the accumulation of excess water and reduce contaminant loads that remain at the end of mining.

Understanding long term residual void hydrology and water quality is an important aspect of effective closure planning (McCullough and Vandenberg, 2020). Integrated water balance and water quality models provide a basis for making decisions regarding water management during operations. Models are also used to identify options and test scenarios for mine closure. There are many promising models to predict water quantity and water quality of residual mine voids (Castendyk, Balistrieri, et al., 2015; Castendyk, Eary, et al., 2015; Salmon, 2017; Maest et al., 2020). Software such as Goldsim® and SEEP are commonly used to examine void hydrology, salinity behaviour and possible groundwater interactions. Additionally, Salmon, (2018) and Morgan et al., (2019) proposed decision frameworks and simplified residual mine void prediction tools that have potential to facilitate more efficient and consistent decisions about planning the rehabilitation of final voids. A difficulty in managing mine water relates to the need to balance extreme climate influence and mine site heterogeneity (Barrett et al., 2017). Water treatment can provide a way to help manage fluctuations from excess to insufficient water and provide a reliable source of good quality water during operations, minimise closure risks and achieve positive outcomes beyond mine closure.

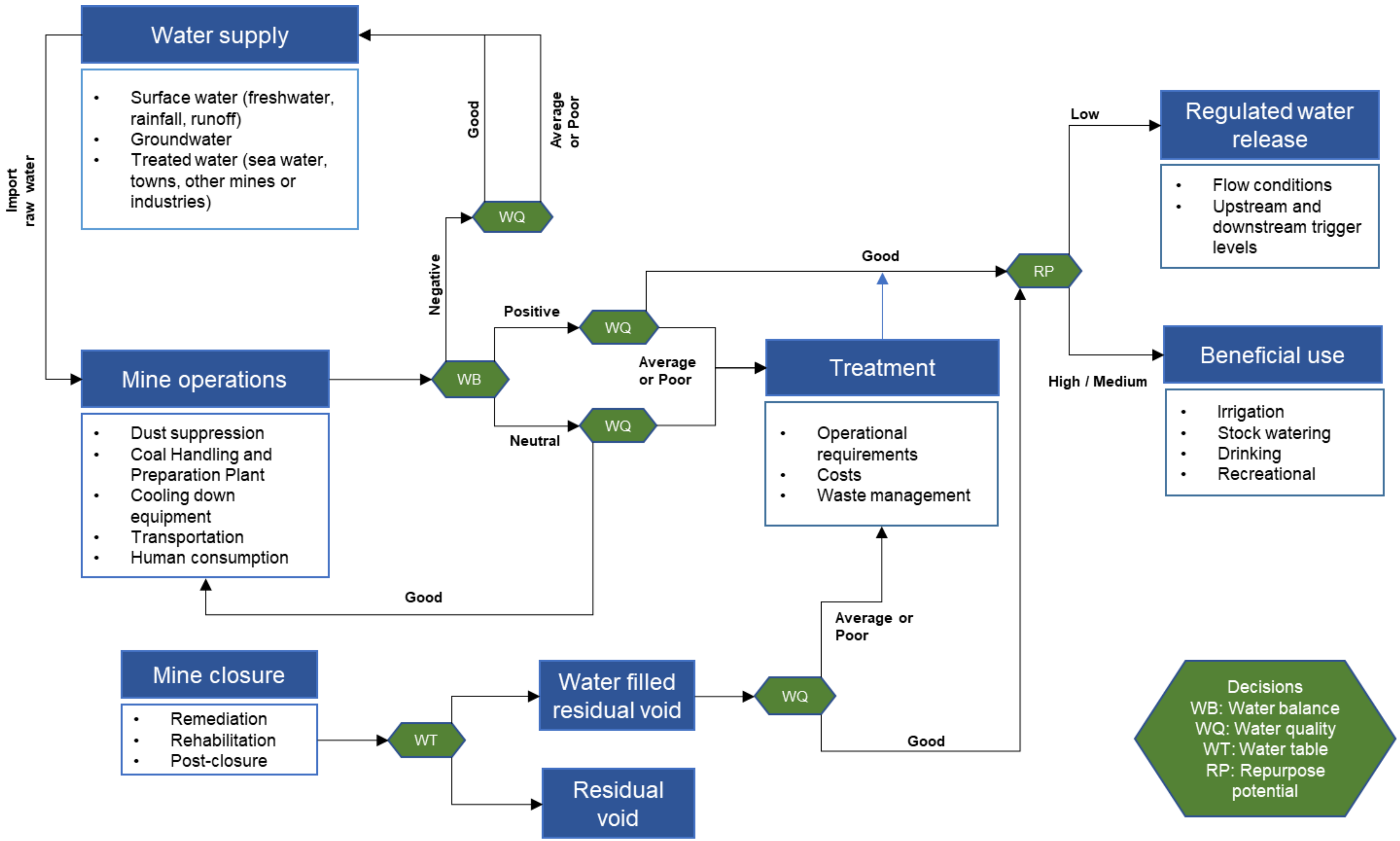

Figure 1. General decision-making framework for water management in mining

3. Treatment requirements for beneficial use

Water is a an extremely important resource to inland and dry regions of Queensland where most of the coal mining projects are located. Leading practice water management including water re-use and recycling has been explored for improving water management (Côte et al., 2008; Barrett et al., 2017). Additional efforts in trading mine affected water have also been investigated, mostly to support operations in drier mine sites (Barrett et al., 2010).

The Coal Seam Gas (CSG) industry in Australia have been pioneering the repurposing of CSG associated water. The CSG Water Management Policy (EHP, 2012) encourages beneficial use in the first instance and then treatment and disposal in a way that protects environmental values. According to the Australian Petroleum Production and Exploration Association, more than 90% of CSG associated water produced in Queensland is treated and made available for beneficial use, mostly in the agricultural industry (APPEA, 2018). The Darling Downs is a key region for this purpose, where receiving treated water increases capacity for irrigated cropping and livestock watering, boosting agricultural production, economic flow-on opportunities, and community benefits (APPEA, 2018). The availability of treated coal seam water has reportedly enabled some irrigators to make very large profits (Monckton, 2019). Studies by Monckton, (2016, 2019) and Monckton et al., (2017) further explore the economic impacts from beneficial use of CSG water in the Chinchilla District.

When it comes to beneficial use of water from coal mine residual voids, a range of potential options may be explored such as recreational facilities (such as Lake Kepwari in Western Australia), wildlife conservation, irrigation, water storage, agriculture, aquaculture, and hydro-electric power generation (McCullough et al., 2020). Examples from southwest Australia have involved restoring former coal mine voids as aquatic ecosystems to contribute to regional ecological values (van Etten et al., 2014). The type of beneficial end use that best suits a location can depend on many factors but water quality is a vital key characteristic on determining successful implementation of a beneficial use (McCullough et al., 2020).

Proactive post-mining land use planning, and residual mine void design should be aligned to provide effective beneficial use of water. Additionally, there is a need to quantify the benefits including cumulative benefits of water treatment in areas where mining is concentrated. In this regard, Table 1 displays guidelines for sulfate and salinity for a range of common beneficial uses. Water quality limits for stock watering and crop irrigation vary according to the species of animal and crop type respectively. The water quality objectives shown are those for the river basin with the most conservative guidelines. The range of aquatic ecosystem protection values shown for salinity represents the most conservative (baseflow) trigger of sub basin water quality objectives within the Fitzroy River Basin and the toxicity trigger reported in the literature. The toxicity guidelines are based on studies undertaken in the Fitzroy River Basin and are not recognised National or State guidelines. The guidelines are described here as a general guide only and the correct guideline for a specific application should be identified according to the procedures described in national (ANZG, 2018) and Queensland water quality guidelines (EHP, 2013c) or other relevant guidance for resource projects. Provision may also be made for deriving a site-specific trigger where required in accordance with relevant guidelines.

Table 1. Electrical Conductivity (µS/cm) and sulfate (mg/L) triggers according to national guidelines and relevant studies.

Beneficial use	EC (µS/cm)	Sulfate (mg/L)	Reference
Stock watering	6,000[a] *(beef cattle)* 3,800[a] *(dairy cattle)* 7,500[a] *(sheep)* 6,000[a] *(horses)* 6,000[a] *(pigs)* 3,000[a] *(poultry)*	1,000[b]	[a] Table 4.3.1 section 4.3.3.5 of from volume 1 of the (ANZECC & ARMCANZ, 2000) as adopted in ANZG (2018) [b] Section 4.3.3.5 from volume 1 of the (ANZECC & ARMCANZ, 2000) as adopted in ANZG (2018)
Crop irrigation	950[c] *(sensitive crops)* 1,900[c] *(moderately sensitive crops)* 4,500[c] *(moderately tolerant crops)* 7,700[c] *(tolerant crops)* 12,200[c] *(very tolerant crops)*	-	[c] Table 4.2.4 section 4.2.4 Soil and water salinity criteria based on salt tolerance from volume 1 of the ANZECC & ARMCANZ (2000) as adopted in ANZG (2018)
Drinking water	900 *(good)* 1,350 *(fair)*	250[d]	[d] Fact sheets on total dissolved solids and sulfate section 10.6 (NHMRC, 2022)
Aquatic ecosystem protection*	310[e] *(base flow)* 2,000[f] (95% species protection)[f]	<5[g] 545 [h] (95% species protection	[e] Water Quality Objectives for the Mackenzie River (EHP, 2013b) [f] Toxicity guidelines for salinity reported in Prasad *et al.*, (2012) [g] Water Quality Objectives for the Comet River (EHP, 2013a) [h] Toxicity guidelines for sulfate reported in Dunlop *et al.*, (2016)
Aquaculture	4,500 (freshwater production)	-	4.4.2 from volume 1 of the (ANZECC & ARMCANZ, 2000) as adopted in ANZG (2018)

Table note: *The Water Quality Objectives (WQOs) scheduled for aquatic ecosystem protection apply and those shown are the most conservative for the Fitzroy River Basin. WQOs vary for sub-catchments across the river basin. The toxicity values reported here are those described in published scientific studies are provided here for indicative purposes but note these do not represent Water Quality Objectives. The triggers described here do not represent the values that are to be applied and instead the approaches described in National and State water quality guidelines are to be used for such purposes.

4. Coal mine affected water quality

Coal mine affected water is defined as water that has come in contact with any area disturbed by coal mining activities, including pit water, processing plant water, rainwater, and runoff. coal mine affected water is likely to contain suspended particulates, ions such as sulfate, salts, grease, oil, and metals (Jones et al., 2019) and coal mine affected water quality varies depending on regional geology. Elevated concentrations of pollutants in coal mine affected water can pose threats to aquatic wildlife in the event of surface or groundwater contamination (Lanctôt, Melvin, et al., 2016). Most coal mining projects in Queensland are located in the Burdekin and Fitzroy Basins, with the latter said to contain 41 operational and historical coal mines authorised to release coal mine affected water (Jones et al., 2019). Though the overburden from coal fields in central Queensland is typically not acid-generating, it can pose a threat to surrounding ecosystems due to elevated sulfate, salinity, and some metals (including but not limited to aluminium, copper, zinc and selenium). Although contaminants of potential concern and concentrations present will vary on a site level, these contaminants are likely to be the major targets for water treatment in coal mine affected water.

The typical parameters for assessing salinity are electrical conductivity (EC) and total dissolved solids (TDS). EC is commonly measured in µS/cm and it indicates the capacity of a liquid to conduct an electric charge, depending on dissolved ion concentrations, ionic strength, and temperature of measurements (Rusydi, 2018). Table 2 shows a classification of six brackish and saline water types proposed by (Rhoades et al., 1992) .

Table 2. Salt water classification according to Rhoades et al., (1992).

Classification		EC (µS/cm)
Brackish		1,500 – 15,000
Saline	*Moderately saline*	15,000 – 25,000
	Highly saline	25,000 – 45,000
	Seawater	45,000 – 60,000
	Brine	60,000 – 85,000
	Hypersaline	> 85,000

A summary of recent literature representing typical salinity measured as EC (µS/cm) and sulfate concentration (mg/L) encountered in coal mine affected water in central Queensland is described in Table 3. Although the available data describes only a sub-set of sites and does not represent the full variation in mine water quality across the Fitzroy River Basin, it gives an indication of observed water quality range at selected sites. The data presented here show the highest EC of coal mine affected water reported in these studies was 7,200 µS/cm, with sulfate observed up to 1,600 mg/L.

Table 3. Typical salinity (µS/cm) and sulfate (mg/L) concentration of coal mine affected water in Central Queensland reported in the literature.

Source	EC (µS/cm)	Sulfate (mg/L)	Collection
Thiruvenkatachari, Younes and Su (2011)	2,765 – 4,457	< 2	5 representative streams within the mine site
Lanctôt, Melvin, *et al.*, (2016)	4,510 – 7,200	150 – 1,600	2 dams authorised for discharge
Lanctôt, Wilson, *et al.*, (2016)	5,900 – 6,980	830 – 1,130	2 dams authorised for discharge
Jones, Vicente-Beckett and Chapman (2019)	175 – 3,300	5 - 477	Provided by company, dams authorised for discharge

Over longer time frames, conservative constituents including salinity and sulfate are most likely to rise in mine affected water storages. Poor water quality can impact closure planning and trigger the need for water treatment. Information describing the predicted long-term salinity of mine voids was obtained from a review of available residual void studies and assessment reports. Information from 13 coal mine sites in Queensland was reviewed to provide an indication of current and predicted mine void salinity. The data presented here describe 37 water filled residual voids, with six additional data points representing sensitivity analyses relating to different climate conditions or different mine void design. In total, 43 data points were analysed with long-term predictions revealing 17 samples that had brackish water and 22 that were saline as per the classification system of Rhoades et al. (1992), see Table 2. Some studies modelled to a point in time where salinity reached equilibrium, while others used a fixed 100 year or nominal timeframe. Figure 2 summarises the data reviewed here that describe predicted salinity concentration in residual mine voids. Figure 2 show predictions are modelled to either equilibrium (9 models) or for 100 years (30 models) into categories of brackish through to hypersaline as per Rhoades et al. (1992).Modelled estimates of the long-term salinity of mine affected water held in residual voids have been predicted to vary considerably, ranging from 1,500 µS/cm up to above 85,000 µS/cm. Data describing predicted sulfate concentration were not described in the reports reviewed here and indicates a gap in current assessment practices.

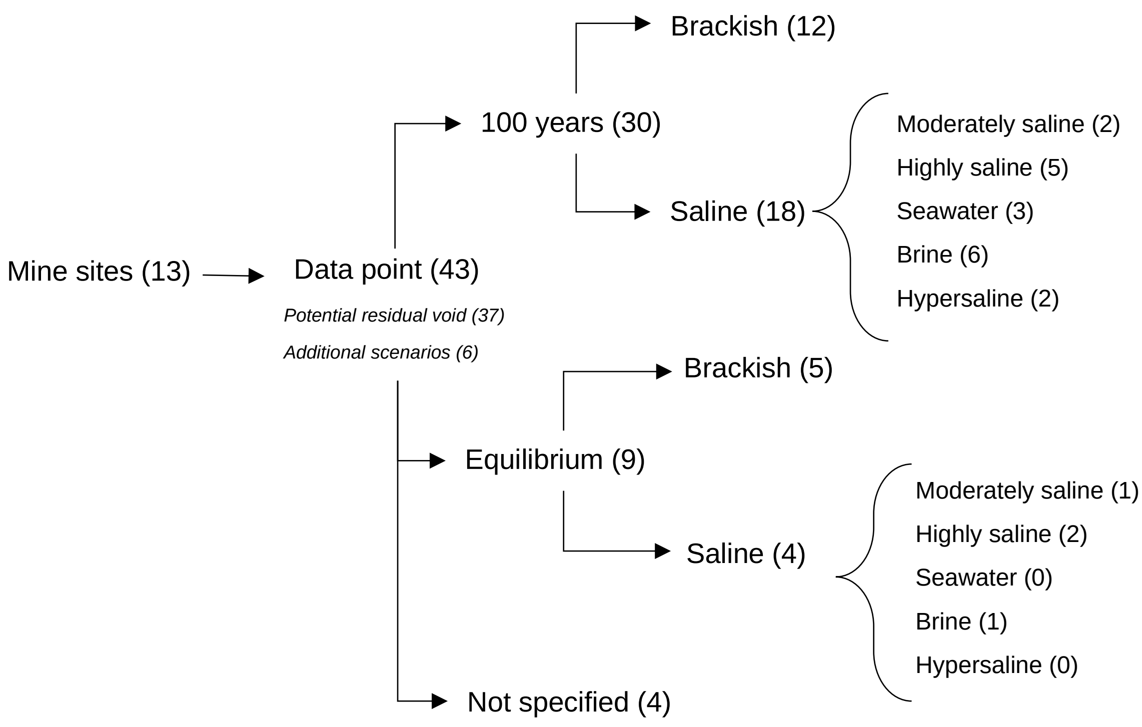

Figure 2. Summary of predicted water quality in residual voids for 13 coal mine sites.

Although a range of different modelled timeframes were presented across the studies reviewed, a subset of that data that reported a modelling timeframe of 100 years was used to provide a basis for comparisons between studies as it was the most reported modelling timeframe. Figure 3 compares the beneficial use thresholds with 100-year predictions of salinity for the 30 data points (see Figure 2) reported from seven mine sites. In Figure 3, sites are shown as A to G, with the number of voids on site indicated (n=3 to 6). Salinity is shown as the Electrical Conductivity (µS/cm) expected to be reached in 100 years on a logarithmic base 10 scale. Indicative beneficial use thresholds for recreational use, aquatic ecosystem (toxicity guidelines for salinity reported in Prasad et al., (2012) are shown for indicative purposes only), irrigation (irrigation A is for moderately tolerant and B is very tolerant crops) and stock watering are shown by dashed lines.The data show that with few exceptions, most of the residual voids will need water treatment to reach water quality guidelines for beneficial use.

There were four data points that reported predictions of long-term EC using varying modelling timeframes (i.e., those described in Figure 2 as 'not specified'). Although the timeframes between those studies vary, they indicated that residual voids are predicted to remain brackish for 20 to 30 years and become hypersaline in the long term with an EC of >85,000 (µS/cm) reached at between 150 to 200 years. Independent of the site that water quality was modelled for, or the format of modelled data encountered, an increase in salinity levels over time was consistently reported suggesting that water quality of coal mine residual voids in Queensland will deteriorate in the long term.

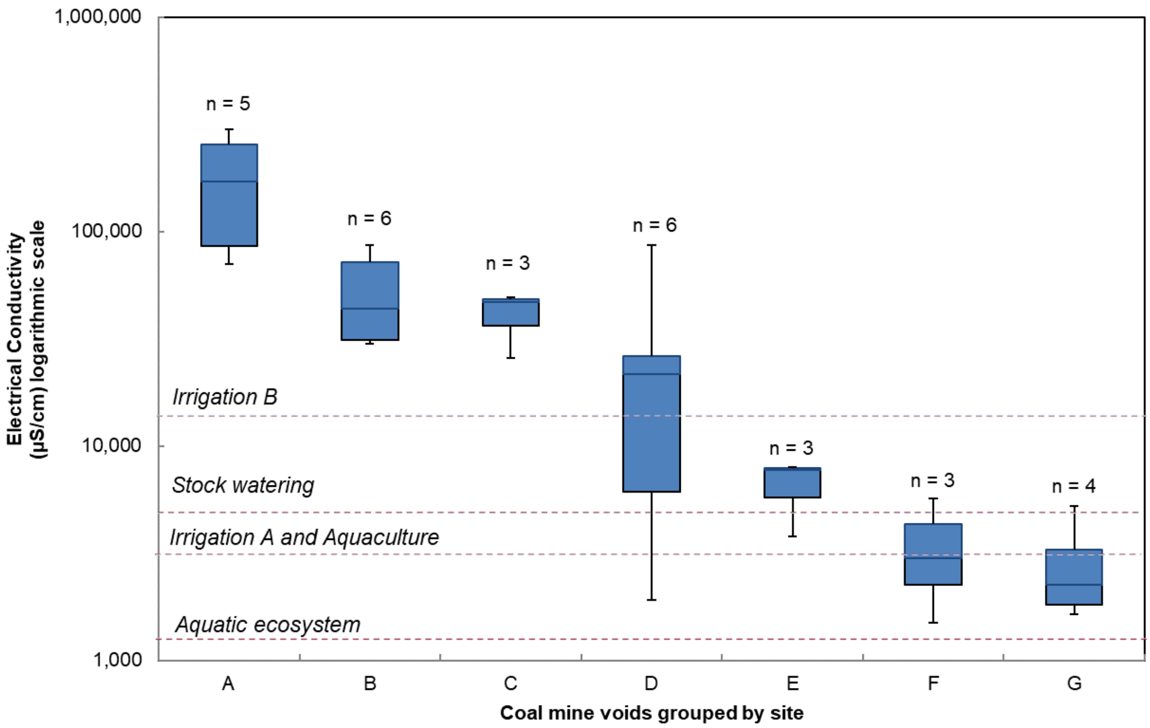

Figure 3. Box plots of salinity predictions across seven coal mines in central Queensland showing the 50th, 25th and 75th percentiles, maximum and minimum.

5. Water treatment technologies for saline water

Water treatment techniques can be categorised into physicochemical, biological, and ecological engineered approaches or a combination of these (Zhao et al., 2020). Physicochemical technologies include mainly thermal techniques, coagulation-flocculation, advanced oxidation process, membranes methods, ion exchange, and electrochemical techniques. Biological treatment methods use a range of biota to treat water, whereas ecological engineered methods involve stabilisation ponds and constructed wetlands (Liang et al., 2017).

Additionally, water treatment processes are divided into pre-treatment, principal, and post-treatment, with all stages contributing to overall performance (Millar et al., 2016; Rebello et al., 2016). The objectives of pre-treatment include removal of coarse and fine particles by screening, filtration, sedimentation and flotation, whereas post treatment is usually a polishing stage targeting specific contaminants where required to treat to a high standard such as drinking water quality. On some occasions, technologies are used as a standalone process but in most cases, water is treated using a combination of techniques.

Although there are many techniques available, the focus of this review was on treatments that are appropriate for saline waters generated from typical coal mines (i.e., acidic, metal-rich water treatment methods were not explicitly considered). These treatment approaches include membrane techniques that are commonly applied including reverse osmosis (RO) and electrodialysis as well as biological methods (including wetlands and biotechnology). These are well-established techniques that are broadly reported and capable of addressing high salinity concentrations (Zhao et al., 2020; Ahmed et al., 2021; Corral et al., 2021; Sahu, 2021).These provide the focus of the review to allow a broad comparison of water treatment options for coal mines and demonstrate an approach to compare the suitability and applicability options. In this regard, the present report focused on technologies being used as principal treatment, but consideration was also given to combining different approaches to water treatment.

6. Other emerging water treatment technologies for saline water

There are also a range of other innovative physico-chemical methods such as ion exchange and chemical precipitation, nanofiltration, membrane distillation and solvent extraction, temperature swing solvent extraction, eutectic freeze crystallisation and thermal crystallisation. These are also briefly described and reviewed.

The combination of nanofiltration, RO, and electrodialysis is used to remove and treat water and recover salts at a pilot plant in at the Bolesław Śmiały coal mine in Poland (van Hooijdonk, 2019). This technology reportedly has a good treatment efficiency but required a high energy usage. A study by Kesieme, (2015) combined two technologies; membrane distillation and solvent extraction to treat mine waste water and recovery of acid. In that study, the author found membrane distillation and solvent extraction was able to concentrate mining waste waters and recover acids effectively. Temperature swing solvent extraction designed to purify hypersaline brines is reportedly able to remove up to 98.4% of salt from a hypersaline solution (Reilly, 2019). This is comparable to the treatment efficiency of RO but does not require high temperatures or high pressures. This technology is radically different to the current techniques because it does not use membranes and is not based on evaporative phase change and instead, uses heat and a low-polarity solvent with temperature-dependent water solubility to remove salts (Boo et al., 2019). Eutectic freeze crystallisation and thermal crystallisation (TC) has also been reported as a useful way to remove salts from solution (Lu et al., 2017; Mazli et al., 2020). There are a range of other crystallisation techniques for treating and recovering salts such as evaporation, cooling, reaction, drowning-out and membrane distillation crystallisation. The advantages and disadvantages of such techniques are discussed further in Lu et al., (2017).

There are also a range of biological sulfate reduction-based bioreactor techniques that have been successfully used to treat mine affected water. Bioreactors use bacterial reduction of sulfate and iron to precipitate metal sulfides (Bowell, 2004; Kaksonen and Puhakka, 2007). Sulfate reducing bacteria can also be used to treat acid mine drainage as a result of biogenic bicarbonate alkalinity (Kaksonen and Puhakka, 2007). A study by Yan et al., (2020) found that combining biological sulfate reduction with hydrotalcite precipitation to treat sulfate rich acid mine affected water was effective in removing more sulfate than the use of hydrotalcite alone. A full review of sulfate removal options for mine water is described in Bowell (2004). They can also have application in a wide range of different types of bioreactors (Kaksonen and Puhakka, 2007). An example is sulfate reducing fluidised bed bioreactors. These have been shown to be technically capable of treating high salt, low pH, metal containing water (Franzmann et al., 2008). A recent study by (Yan et al., 2020) also found that combining biological sulfate reduction with hydrotalcite precipitation to treat sulfate rich acid mine affected water was effective in removing more sulfate than the use of hydrotalcite alone. Although bioreactors have been used in metal rich waters, their application in saline coal mine affected water with low metal concentration has not been well described and may be limited.

7. Membrane techniques

7.1 Reverse osmosis

Reverse osmosis (RO) technology has good capacity to remove contaminants including salinity and sulfate commonly associated with coal mine affected water compared with all other conventional pressure-driven membrane techniques (i.e., microfiltration, ultrafiltration and nanofiltration). Municipal desalination plants and the CSG industry in Australia (Surat Basin) and in the USA all use RO as the principal treatment method to beneficiate their affected water (USEPA, 2014; Rebello et al., 2016; APPEA, 2018). Although it is a versatile technology capable of reducing the concentration of many contaminants simultaneously, RO has high set-up and operational costs that occasionally limit its large-scale application. Brine rejected from RO requires management and disposal, and pre-treatment steps are typically used to minimise energy costs and maximise membrane lifespan (Pinto et al., 2016).

7.1.1 Technology and operation description

The main component of RO is the semi-permeable membrane that allows pure water to pass through while removing contaminants by size or charge exclusion and through solute, solvent, and physicochemical interactions (Pinto et al., 2016). Durable membranes have to be resistant to chemical and microbial agents and can be set in an array of arrangements (single or multiple layers, spiral-wound or hollow fibres) depending on the specific goals and characteristics of the affected water to be treated. These membranes differ in hydrophobicity, charge, and surface morphology, being configured as flat sheets and folded over a porous spacer (Figure 4) (Khan and Kordek, 2014;

USEPA, 2014; Pinto et al., 2016). Figure 4 is reproduced from 'Coal Seam Gas: Produced Water and Solids', Khan and Kordek, (2014) with permission from Professor Stuart Khan.

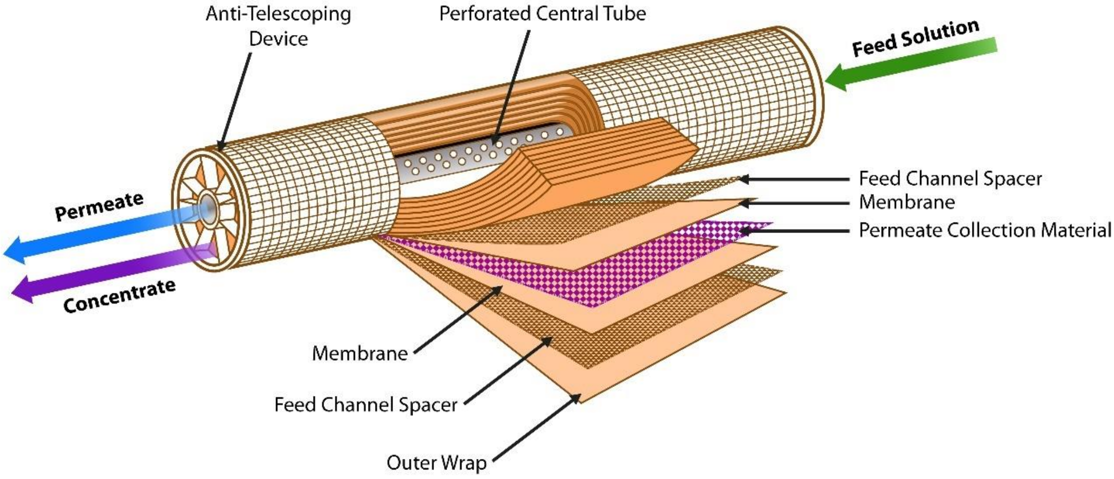

Figure 4. Membrane configuration of the reverse osmosis process.

The perforated tube carries the clean water known as permeate that passes across the membrane and travels through the porous spacer and a concentrated brine solution is removed and requires management or disposal (Khan and Kordek, 2014; USEPA, 2014). In industrial applications, RO can be combined with other techniques (adsorption, ion-exchange, precipitation) as pre-treatment or even two RO stages to reach drinking water quality standards, minimising brine volume and increasing water recovery rates (Rioyo et al., 2017).

7.1.2 Effectiveness

Factors directly affecting the effectiveness of RO include solute concentration, pressure applied, water flux rate, and membrane and feed water properties (Pinto et al., 2016). For large scale plants, the general RO water recovery has been reported to vary within 50–90% of the total treated water volume, with some specific cases or small pilot plants reporting 95-99 % recovery (USEPA, 2014; Thiruvenkatachari et al., 2016, 2020; Runtti et al., 2018; Sahu, 2021). Total dissolved solids removal of 90-99% can be routinely achieved (Khan and Kordek, 2014; Rioyo et al., 2017).

7.1.3 Limitations

The primary constraints for RO are the relatively high costs and essential pre-treatment requirements combined with its operational complexity and the need to manage brine waste. Plant installations require specific and expensive materials and the process uses substantial energy to generate the pressure responsible for forcing the affected water through the membrane, increasing capital and operational costs (Khan and Kordek, 2014; USEPA, 2014). Pre-treatment considerations are mandatory to reduce operational hazards such as membrane scaling and fouling that will affect process efficiency and shorten membrane lifetime (USEPA, 2014; Runtti et al., 2018).

Approaches used to dispose of brine solution include evaporation, encapsulation, deep well injection, disposal in a waste facility or ocean discharge. Brine disposal can increase the overall cost of the project (USEPA, 2014; Mansour et al., 2017; Katal et al., 2020). For inland areas, however, plants operate at high recovery rates to minimise the volume of brine to be discharged, facilitating disposal or even having a zero liquid discharge (Rioyo et al., 2017). Further complexities of RO involve frequent membrane monitoring and maintenance required to ensure effective operation. In the past, Australia suffered a shortage of experienced operators to support the extensive desalination industry applied to mining operations (Moran and Moore, 2005). RO treatment plants can have high construction and operating costs, with energy consumption strongly affected by the feed concentration of dissolved solids and subsequently required osmotic pressure (USEPA, 2014; Runtti et al., 2018). The investment will also depend on the capacity and treatment rate.

7.2 Electrodialysis

Electrodialysis (ED) is another membrane technology but differs from RO as it does not require the use of high pressures. Instead, it drives the process via electric fields for highly efficient ion separation (Mustafa et al., 2021). For over 60 years, ED has been an established technology in treating industrial wastewater, brackish water, municipal wastewater and is used in drug and food industries, chemical processes and table salt production (Al-Amshawee et al., 2020). This technology has emerged as a strong competitor for RO in the treatment of saline waters for potable purposes and there have recently been major improvements in pre-treatment requirements and cost structure (Firth et al., 2002; Fell, 2014). To date, great advancements have been achieved in developing innovative ED arrangements, like the promising reverse electrodialysis (RED) that provides optimum operational conditions (Mei and Tang, 2018).

7.2.1 Technology and operation description

The operation of ED is driven by the development of ion-exchange membranes (IEMs) that produces high water recovery and do not require phase change, reaction, or chemicals (Al-Amshawee et al., 2020). The selective transport of ions through charged membranes is caused by applying an electrical field (Runtti et al., 2018). In some cases, salinity gradient power can instead be used to extract power due to RED. RED is a variation on the ED process, which uses electrode polarity reversal to automatically clean membrane surfaces, but both processes work in the same manner. When the polarity is reversed, the source water dilutes and concentrate compartments are also reversed, and so are the chemical reactions at the electrodes. This process uses the chemical potential difference between solutions and their salt content separated by IEMs, creating chemical energy that is converted into electrical energy using appropriate electrodes (Zoungrana and Çakmakci, 2021). This polarity reversal helps prevent the formation of scale on the membranes (Sahu, 2021). Figure 5 illustrates ion exchange membranes (IEMs) assembled in a typical RED stack. Figure 5 is reprinted from Desalination, Volume 425, Mei and Tang (2018), ‘Recent developments and future perspectives of reverse electrodialysis technology: A review’, Pages 156-174, copyright 2017, with permission from Elsevier.

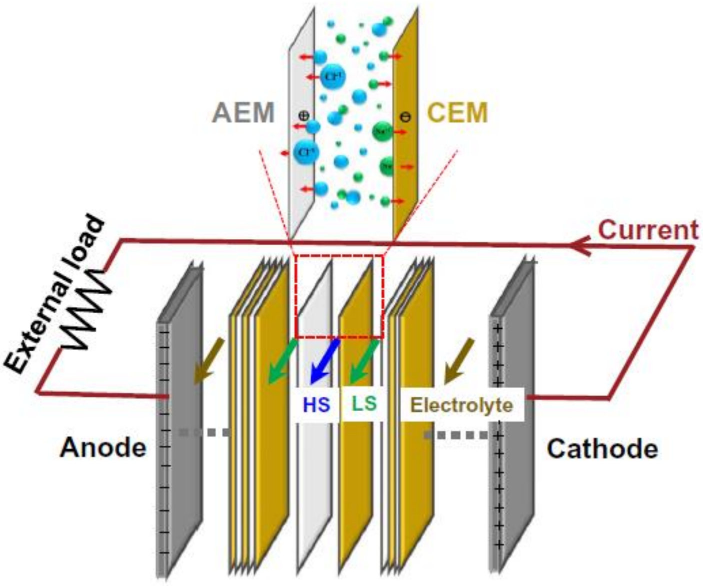

Figure 5. Reverse electrodialysis (RED) stack connected to an external electric load showing cation exchange membranes (CEM) and anion exchange membrane (AEM) with high salinity (HS) and low salinity flow streams (LS).

IEMs are divided into cation exchange membranes and anion exchange membranes alternately stacked to create a series of adjacent high concentration compartments and low concentration compartments fed with high concentration solutions and low concentration solutions, respectively (Tufa et al., 2018). The typical waste stream flow requiring disposal will be the concentrate, electrode cleaning flows, and residuals from the pre-treatment (Sahu, 2021).

7.2.2 Effectiveness

Large-scale ED plants are becoming frequently cited in the literature, mostly treating brackish water or RO brine and reaching up to 85% freshwater recovery rates when initial salinity is 2,500-3,000 mg/L (Al-Amshawee et al., 2020; Sahu, 2021). Moreover, its rapid development has allowed further scalability and processing of brackish water having salinity above 15,000 mg/L, with some authors suggesting that ED might have an economic advantage over RO for waters with total dissolved salts as high as 10,000 mg/L (Burn et al., 2015; Al-Amshawee et al., 2020). When it comes to RED, there are still some challenges to overcome. Despite having greater performance than RO when treating saline water high in silica, RED still lacks commercial large scale demonstration (Thiruvenkatachari et al., 2011; Fell, 2014). Zoungrana and Çakmakci (2021) reported energy losses to hinder the possibility for large scale installation. Mei and Tang (2018) report that pilot plants for RED have been commissioned in the Netherlands and Italy.

7.2.3 Limitations

ED and RED have potential for removing salinity and there are examples where it has successfully been scaled up for use in industrial applications including in the Netherlands and Italy (Mei and Tang, 2018), Australia (Taylor and Goodman, 2007) and India (Keri et al., 2011). However, it currently only represents less than 5% of installed desalination capacity worldwide (Shemer and Semiat, 2017). Like RO, the main limitations are the cost, membrane performance and need for brine management (Al-Amshawee et al., 2020). Walha *et al.*, (2007) found that ED can reduce desalination costs when compared with RO, but it depends on the characteristics of the saline water to be treated.

7.3 Case studies - membrane techniques

Innovation is required to address the cost barriers, membrane fouling and scaling challenges, and the generation of by-products from RO, ED, and RED that might limit their uptake for treatment of coal mine affected water. To increase their attractiveness, many authors (e.g. Burn et al., 2015; Mei and Tang, 2018; Mito et al., 2019; Al-Amshawee et al., 2020; Ahmed et al., 2021) have systematically suggested reducing costs by improving membrane robustness, using alternative energy sources, and employing innovative pre-treatments to remove specific contaminant and reduce fouling.

One of the strategies to overcome membrane fouling and scaling is developing new highly selective, conductive, and cost-effective materials. In this regard, (Shenvi et al., 2015) suggested nano-structured membranes involving thin-film nanocomposite membranes, carbon-nanotube membranes and aquaporin-based membranes like the ones presented by (Gray et al., 2010), (Gumbi et al., 2017) and (Seo et al., 2018). Alternative feed solutions and innovative arrangements with integrated pre-treatment approaches have been reported to have potential on reducing costs, increasing contaminant removal, and improving overall performance of membrane techniques (Zhu, 2012; Altaee et al., 2018; Mei and Tang, 2018; Zoungrana and Çakmakci, 2021).

Forward osmosis (FO) has received extensive attention during the last decade as an emerging technology for water re-use and seawater desalination (Chung et al., 2015; Sawaki and Chen, 2021). The difference between RO and FO is that in the FO, water is induced to move naturally across the membrane by differences in osmotic pressure. The high salinity solution acts as the draw solution, with a higher osmotic pressure than the wastewater to be treated. Because there is no outside pressure forcing the water through the membrane, FO requires less energy than RO but the final product it is not potable water. Instead, it is used as a diluted draw solution, a mixture of the respective draw and wastewater solutions, which, depending on water re-use purpose, may require further treatment to extract clean water and to regenerate the draw solution (Chung et al., 2015). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Coal Association Research Program (ACARP) are carrying out studies using FO as a pre-treatment for RO in the context of treating coal mine affected water (Thiruvenkatachari et al., 2020). The authors trialled and demonstrated this new approach in 2020 at a NSW coal mine site treating 10 m^3/day. Results have shown this arrangement is capable of greatly improving water treatment by obtaining 90-95% water recovery with 85% and 99% reduction in EC and sulfate, respectively.

An alternative approach that has been investigated to reduce operational costs is the use of renewable energy to power RO (Calise et al., 2019; Mito et al., 2019) and RED plants (Malek et al., 2016; Zoungrana and Çakmakci, 2021). However, the capital outlay to support such initiatives and lack of large scale studies demonstrating its use are still discouraging to investors (Loutatidou et al., 2017). An emerging approach is generation of renewable energy from a salinity gradient, but the applicability in a natural environment can be challenging (Duarte and Bordado, 2016; Tufa et al., 2018; Zoungrana and Çakmakci, 2021).

8. Biological methods

8.1 Constructed wetland

Constructed wetlands (CWs), also known as artificial wetlands, are artificially engineered ecosystems that have been used for treating municipal, domestic, agricultural, and industrial wastewater since the early 1950s (Zhi and Ji, 2012; Austin and Yu, 2018; Opitz et al., 2021). In the mining industry, they are used to passively remove a variety of mine water contaminants such as acidic mine affected water, metals and sulfate (Fernando et al., 2018). However, CWs do not typically provide an effective means to remove salt from saline wastewater. CWs can be designed as aerobic wetlands, anaerobic horizontal-flow wetlands, and vertical-flow ponds (also known as vertical-flow wetlands) to treat contaminants over a long period through plant uptake, volatilisation, and biological reduction (USEPA, 2014). Wetlands are a versatile treatment technique and can be used as the sole treatment technology or added on to other treatment systems. When compared with other methods, CW has the advantage of relatively low set up cost, low energy use and consumables requirements (USEPA, 2014; Fernando et al., 2018). However, despite the promising use of CWs, more research is needed regarding design, operation, and optimisation of CWs for treatment of saline wastewaters (Liang et al., 2017) such as those present in a typical Queensland coal mine context. A review by Liang et al., (2017) indicated that the presence of salts in saline wastewater often negatively impacts the performance of CWs to remove nutrients and metals by inhibiting the function of plants, microorganisms and even substrates. As a result, salt tolerant plants are required (e.g., halophytes or salt-tolerant plants) in wetlands where seeking to remove contaminants from saline water. In some instances, accumulation of contaminants in wetlands may require maintenance to remove contaminant build up.

8.1.2 Technology and operation description

CWs integrate several components such as plants, substrate or support media and microorganisms (Jesus et al., 2014). The main component of CWs for contaminant removal are wetland plants that can directly assimilate nutrients and accumulate heavy metals into their tissues, moderating hydrological conductivity, transporting O_2 through leaves, and secreting chemicals as catalysts in the rhizosphere. Additionally, they can provide adsorption sites for microorganisms, indirectly contributing to the removal of metals and maintaining structural and functional integrity (Liang et al., 2017).

The structure of a CW consists of an insulated pond filled with permeable materials, such as sand and gravel, in which contaminant-resistant plant species are used.

Figure 6 shows the flow patterns of a subsurface CW, in which the flow runs beneath the surface of the porous substrate and may be one of two types: either a horizontal or vertical subsurface flow. There is also free water surface flow CWs, in which wastewater flows on the surface of the porous substrate.

Figure 6 is reproduced from USEPA, 2014 ‘Reference guide to treatment technologies for mining-influenced water' with permission from the United States Environmental Protection Agency (USEPA).

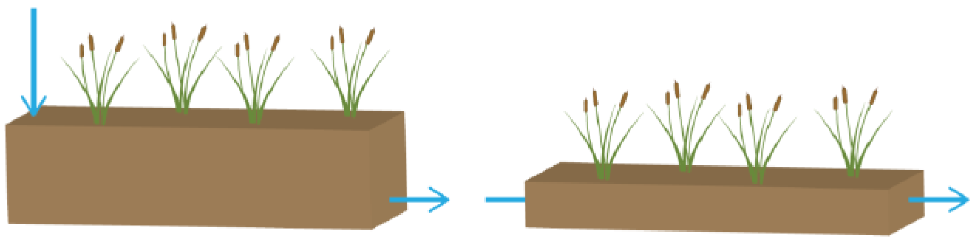

Figure 6. Simplified conceptual model of flow patterns in constructed wetlands.

Among the most important design considerations are loading rate retention time, slope, substrate, vegetation, sediment control, geometric configuration and seasonality (USEPA, 2014). A major constraint for CWs in treating high salinity wastewaters is that salt tends to inhibit conventional biological treatments (Jesus et al., 2014). In this regard, efforts have been made in using halotolerant or halophytic plants capable of thriving and reducing contaminants (such as metals and nutrients) even in high salinity wastewaters (Jesus et al., 2017).

8.1.3 Effectiveness

Despite plants having different salt tolerance mechanisms, which impact treatment efficiency, CWs show potential in treating saline wastewater (Farzi et al., 2017; Xu et al., 2019). Also, seasonal variations in removal efficiency have been noted, with lesser amounts of target contaminants expected to be removed in cold weather and aerobic CWs being generally more effective and performing best at low flow rates (USEPA, 2014). It has been reported that sulfate removal can vary from 10-30% for coal mine drainage and metal mine drainage (USEPA, 2014). Many other authors have observed salinity reductions of innovative CWs systems ranging from 15-60% when treating other industrial effluents (Jesus et al., 2014, 2017; Yang et al., 2015; Farzi et al., 2017; Xu et al., 2017). Unfortunately, there is not a wide range of studies that have tested CWs performance under high salinity conditions with potential for both salt and sulfate removal.

8.1.4 Limitations

Despite their minimal costs, convenient operation, eco-friendly characteristics, and aesthetic value, CWs have several constraints (Corral et al., 2021). First, they require a relatively large amount of land per unit volume of water with usually a low treatment rate. CWs implementation requires an initial construction cost and upfront monitoring to make sure the system is functioning and stable. Local seasonality is an important factor in wetland design. Wetlands treat water at a slower rate compared with active treatment technologies (USEPA, 2014). Secondly, CWs need a constant and sufficient supply of water to support plant and microorganism growth, which can be a problem in semi-arid regions. Lastly, despite their passive management nature, the periodic release of captured contaminants may occur during high-flow periods or periods when vegetation decomposes (Werellagama and Karunaratne, 2011; USEPA, 2014).Although some general guidelines have been developed over the years, wetland construction is not as well "defined" as it is with the more mechanised systems (Karunarathna, 2011). Nonetheless, CWs are widely regarded as the best low-cost alternative eco-technology for the treatment of municipal, industrial, and agricultural effluents (Jayakuma and Dandigi, 2004). A major part of the capital expenses required for the installation of CW systems is as follows in order of their importance: land, excavation, stuffing material, piping structure, vegetation and other activities. A study by Gunes *et al.*, (2011) provides further information on construction and maintenance costs for horizontal-free surface flow wetlands treating mostly municipal and domestic wastewater.

8.2 Biotechnological treatment

Biotechnological treatments (BTs) are able to remove pollutants from wastewater. These can be economical, highly effective, stable and environmentally friendly (Zhao et al., 2020; Nagda et al., 2022). This technique has been extensively used for treating municipal and industrial wastewaters like seafood processing, leather, and textile effluents (Sharghi et al., 2013; Jeddi et al., 2020). In the mining industry, they are largely applied to treat acid mine drainage and reduce sulfate (Wielinga, 2009; Thiruvenkatachari and Su, 2017).

A range of literature (Tomei et al., 2017; Tan et al., 2019; Capodici et al., 2020; Corral et al., 2021; Zoomi et al., 2021), explores halotolerant microorganisms applying salt exclusion strategies to treat saline effluents. This mechanism reduces other contaminants, but it does not alter the salt concentration of the external environment, offering little opportunity to reduce salinity levels. In this regard, a relatively new and innovative approach known as biodesalination has been described in some recent studies that investigated the potential of using microbial biosorption and bioaccumulation mechanisms to remove dissolved salts and reduce salinity levels (Taheri et al., 2016; Puspaningrum and Titah, 2020; Barahoei, Hatamipour and Afsharzadeh, 2021; Kumar Patel et al., 2021).

8.2.1 Technology and operation description

Biodesalination is a relatively new field that resulted from the need to address the problems with traditional desalination processes through the application of promising findings regarding microorganism adaptability (Taheri et al., 2016; Azmi et al., 2018). It involves taking benefit from organisms that uptake or adsorb salts and harvesting the biomass for removal. This field is still in its infancy, and there is a range of mechanisms that could be used to reduce salinity levels (Gao et al., 2017; Azmi et al., 2018; Wei et al., 2020; Do et al., 2021; Kumar Patel et al., 2021). For instance, intracellular salt accumulation, also known 'salt-in strategy' in which microorganisms balance their cytoplasm osmotically with their surrounding environment. However, most of the microorganisms that apply this strategy are frequently obligate halophiles and have poor survival rates at salinities lower than seawater, which may hinder their ability to reduce salinity levels to acceptable guidelines. Biosorption is the primary route by which some algae have been shown useful for biodesalination (Sahle-Demessie et al., 2019). Passive biosorption of salts, rather than active uptake also offers an opportunity for biodesalination from a wide range of microorganisms. Microbial cell walls contain proteins, polysaccharides and lipids that give the cell wall an overall net negative charge and offer an excellent cation binding capacity.

8.2.2 Effectiveness

A review by Kumar Patel *et al.*, (2021) found that under optimum conditions, algae-based biodesalination can effectively remove 50–67% of salts present in saline water. But there are countless arrangements and parameters that can influence biodesalination performance. For instance, Figler *et al.*, (2019) obtained up to 39% conductivity reduction using halotolerant green microalgae to treat artificial effluent with different NaCl concentrations (500 – 20,000 mg/L). Sahle-Demessie, Aly Hassan and El Badawy (2019) used a photobioreactor to demonstrate 30% NaCl removal from brackish (4 g/L NaCl) water but highlighted limited desalination at 20 g/L and unsuccessful upscaling. Azmi *et al.*, (2018) used cyanobacteria to reduce salinity by 30-52%, whereas (Barahoei, Hatamipour and Afsharzadeh, 2021) results indicated EC removal efficiency varying from 30-80% for an initial salinity range of 1000-5000 mg/L.

8.2.3 Limitations

Research into biodesalination is rapidly advancing as it has been shown to provide an effective means to reduce effluent salinity in a cost-effective manner. However, advancements achieved so far are primarily at laboratory or small scale. The main challenges related with upscaling the technology are expected to be reduced efficiency and complications with biomass growth (Kumar Patel et al., 2021). There is a lack of comprehensive life cycle assessments evaluating the large-scale feasibility of biodesalination, or its long-term advantages and disadvantages (Sahle-Demessie et al., 2019; Zhao et al., 2020). The relative costs of biodesalination are difficult to gauge and may depend on the application. However, there is potential for beneficial use of algal biomass as a livestock feed supplement or source of bioenergy (Amezaga et al., 2014; Do et al., 2021).

8.3 Case studies - biological techniques

One of the remarkable and innovative biodesalination approaches is known as microbial desalination cells (MDCs), in which photosynthetic modified cells can not only desalinate saline water but are also able to generate electricity (Taheri et al., 2016; Barahoei, Hatamipour, Khosravi, et al., 2021; Corral et al., 2021). This method, however, demands high salinities to work and needs a source of organic matter to generate the bioelectric current (Carmalin Sophia et al., 2016), which may hinder its immediate application in treating coal mine affected water.

9. Comparing water treatment options

This section describes the criteria used here for assessing the suitability and feasibility of using water treatment to improve the quality of saline coal mine affected water. In this regard, suitability refers to a treatment technique's appropriateness to reduce the salinity of the affected water, and feasibility refers to its potential to be implemented at a given mine site.

Figure 7 displays the framework developed and explores water treatment processes in the mining industry. Figure 7 shows an assessment process that is represented as headings in the coloured boxes and variables are listed as bullet points in the below white boxes. Green hexagons illustrate decision-making steps when assessing resource re-use potential or variable requirements (legend in figure shows definition of acronyms).

9.1 Results

Variables in the criteria framework were classified as high, medium, or low according to their necessity or performance. The classification was based on information gathered from the literature review on water treatment techniques and in some instances a ‘best-case’ scenario was assumed to simplify comparisons. Table 4 describes the criteria uses to assess the ‘suitability’ and ‘feasibility’ of treatment options assessed against each of variables according to H = high, M = medium, L = low, A = active, P = passive. Table 4 displays results of the assessment of treatment options in terms of their suitability and feasibility in treating coal mine affected water in residual voids. RO consistently outperformed other techniques, except when considering final waste disposal and cost (Table 4). There was a similar pattern with ED/RED that presented modest advantage with regard to costs when compared to RO. CWs and BT presented advantages in terms of costs and waste management but when it comes to operational requirements, these techniques ranked lower than RO and ED/RED. It is important to note that the suitability and feasibility ratings assigned here are of a general nature and are only used demonstrate the approach to assess and compare treatment options.

9.2 Limitations

Technologies were assessed at the principal stage of the water treatment process. However, considerations regarding pre-treatment and polishing stages are also important and would need to be addressed in further research and considered in decision-making processes. Also, due to the heterogeneity of available data and conditions in which treatments were applied, the information described here provides a general qualitative comparison between technologies. Ideally a quantitative comparison between treatment technologies would be made in practice. Such an approach was not possible in this study as there was insufficient information for all technologies available to allow this.

It was necessary to define general groups of treatment technologies for the purpose of this study. The grouping of treatment technologies into the categories used here (as described in Table 4), may influence whether a treatment option may be considered suitable or not for treating one or more contaminants. For example, the use of sub-categories for the treatment types described here would provide greater resolution when evaluating the treatment types and may have different results when considering the ability to remove specific contaminants, achievable treatment rates, inputs required and scalability. Accordingly, the results presented here are not intended to be applied at a site level and instead are presented to demonstrate the approach to assess and compare treatment options.

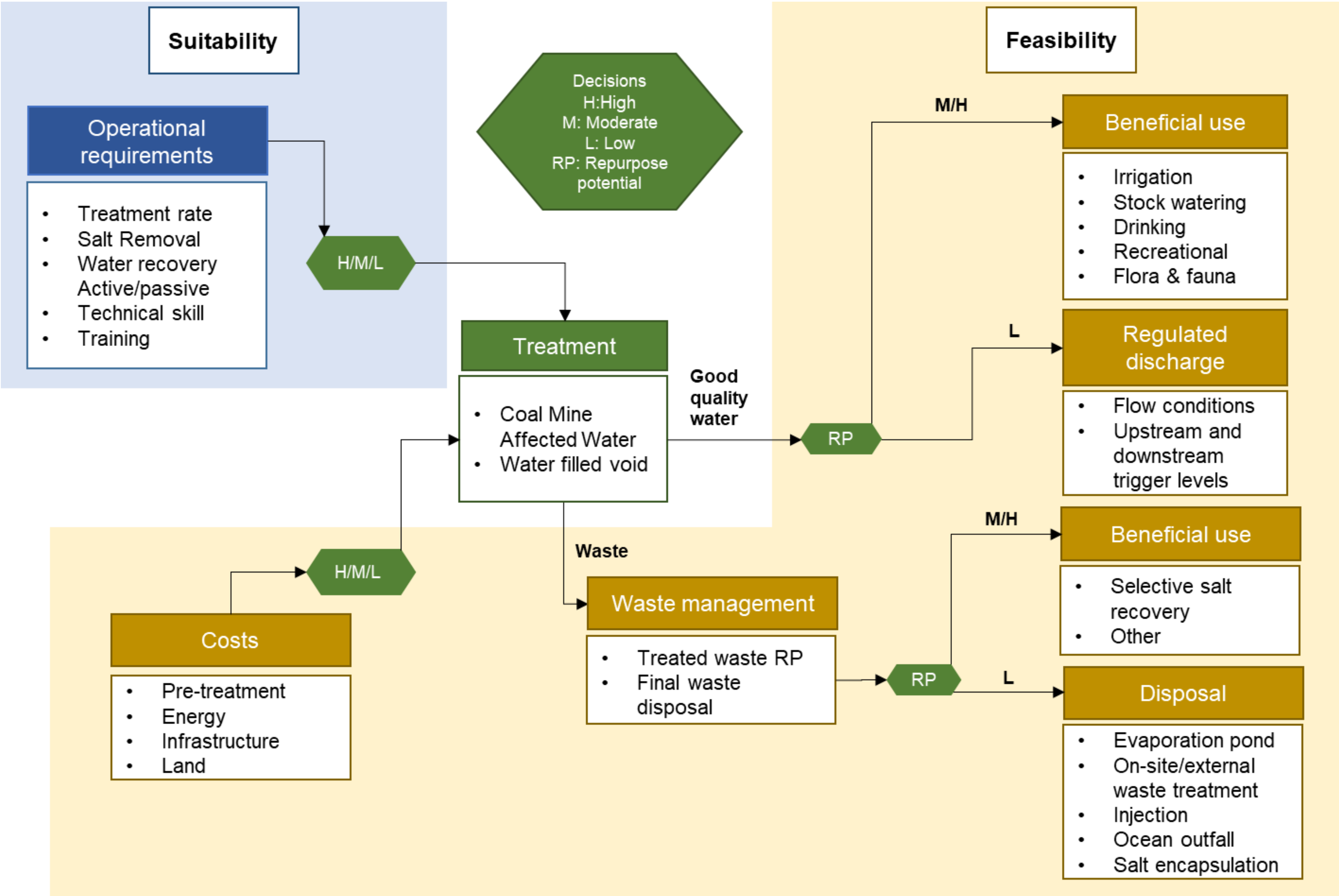

Figure 7. General flowchart exploring the role of water treatment processes in the mining industry.

Table 4. Summary of treatment options from coal mine affected water, assessed by the proposed criteria framework above.

Analyse	Criteria	Variable	Treatment option			
			RO	ED/RED	CWs	BT
Suitability	Operational requirements	Treatment rate	H	M	L	M
		Water recovery	H	H	M	M
		Salt removal	H	H	L	M
		Input/maintenance	A	A	P	A/P
		Training and technical skill	H	M	L	M
Feasibility	Costs	Pre-treatment	H	M	M	M
		Energy	H	M	L	L
		Infrastructure	H	H	L	M
	Waste management	Final waste disposal	H	H	N/A	L
		Treated waste re-use potential	-	-	N/A	L
	Beneficial use	Treated water re-use potential (*requires site specific consideration*)	H	H	L	-

10. Discussion

The suitability analysis provided insights regarding which technology might be useful at the operational stage compared to technologies that are more likely to be applied post-mining. For instance, the strictly active methods of RO and ED/RED are capable of operating with high treatment rates, high water recovery and high contaminant removal rates. RO is a well-established process and is able to reliably generate high volumes of good quality, but the disposal of mixed salt presents a problem that requires further evaluation (Shi et al., 2020). Because of this, RO and ED/RED are likely suitable in a closure scenario with high contaminant loading and high volume of water to be treated. However, the disadvantages of using these approaches are that they require high levels of training and technical skill to operate. Also, the substantial energy and consumables requirements combined with active input, maintenance needs, and waste generated may lead to impracticalities when applied in remote areas.

Contrary to this, CWs and BTs seem to be pertinent approaches to use in remote areas in terms of input and maintenance needs. CWs are mainly a passive method that requires short attention in the beginning for structure implementation and ensuring plants and microorganisms will survive. But apart from that, no intensive input and maintenance or training and technical skills are required. The same happens with bioreactors that can be designed to be active or passive. However, when it comes to treatment rate, water recovery, and contaminant removal, CWs and BTs may be sensitive to variability in water quality and environmental factors. Therefore, unless contaminant concentration and the volume of water requiring treatment are low, these technologies may not be robust enough to reliably treat legacy issues in practice at large scale.

In terms of feasibility, all methods presented positive and negative characteristics, which leads to applicability being intrinsically related to mine location and regional dynamics. Pre-treatment requirements are a vital variable that will impact the overall performance of all treatment methods assessed. But pre-treatment primarily relates to RO since its efficiency and costs are considerably impacted by the process chosen to ensure that the water to be treated meets membrane lifespan requirements. Other variables varied between treatment methods leading to possible trade-offs.

On one hand, when it comes to infrastructure and energy required to operate, the active technologies assessed (RO, ED and RED) presented greater necessity than the others (CWs and BT), which is reflected in their higher costs of investment. BT will also need some sort of infrastructure but is not as demanding as RO and ED/RED in this regard. The waste stream is a major concern for RO and RED since both technologies generate highly saline brine that needs appropriate disposal management. Common strategies for brine disposal are injection, ocean outfall, encapsulation, and selective salt recovery (APPEA, 2018). Brine management increases project investment and needs to be taken into consideration when planning the life of a water treatment plant. Other feasibility criteria considered in the framework but not evaluated were treated water and treated waste re-use potential. The influence of these features depends on factors specific to each mine site such as its location, climate, weather, and regional dynamics evaluated.

Overall, all treatment technologies evaluated offer advantages and disadvantages, and trade-offs need to be considered case-by-case. In this regard, Table 5 provides a snapshot of water treatment advantages, limitations, and research prospects for coal mine affected water in Queensland. Some authors have developed guiding flow diagrams for saline effluent management and decision trees to select appropriated treatment technologies (Corral et al., 2021; Sahu, 2021). Both frameworks tend to explore biological technologies in treating saline effluents first, given their low cost and simplicity. The same principle could be applied for treating saline water from coal mine voids, as long as the approaches can be successfully applied to meet large scale demands and the quality of treated water is suitable for its intended use.

Table 5. Advantages, disadvantages, and prospects for water treatment techniques for saline coal mine affected water adapted from Sahu (2021) and Srivastava et al., (2021).

Treatment	Advantages	Disadvantages and limitations	Future research prospect
RO	• Highly efficient in reducing salinity • Commercially well-established method	• High capital outlay and operational costs • Membrane fouling and scaling complications • Requires training to operate • Requires by-product disposal	• New membrane materials • Reduced cost when paired with FO • Renewable energy sources can reduce associated energy costs
ED/RED	• Highly efficient in reducing salinity • Potential for energy generation	• Problems with efficiency in large-scale projects • It can become cheaper than RO • Requires by-product disposal	• New membrane materials (including nano technology) • New treatment arrangements • Renewable energy sources can reduce associated energy costs
CWs	• Less costs • May require maintenance to remove contaminants • Ecological and aesthetical co-benefits • Passive method	• Inefficient for desalination particularly in low-nutrient situations • Slow rate of removal • Requires large area of land	• Halotolerant plants capable of reducing salinity
BTs	• Great potential to reduce salinity • Active or passive method • Potential for beneficial use of harvested biomass	• Changing salinity levels may hinder microbial growth and reliable performance • Need to harvest and remove biomass	• Biodesalination • Microbial desalination cells • Potential energy source

11. Conclusion

An analysis of current and predicted salinity levels in coal mine voids in central Queensland showed that salinities are typically high and the water will not generally be suited for beneficial use without treatment. A review of water quality modelling estimates show salinities of water in coal mine voids is expected to increase into the future. Proactive treatment of mine affected water during mining and after closure provides an opportunity for beneficial use of the water. This study developed and described an assessment framework that can be used to evaluate and compare water treatment techniques for coal mine affected water. The study also provides a general qualitative comparison of the main operational parameters and requirements between treatment options considering the best possible scenarios that can be achieved. Overall, there is no single technology that will fit all cases, but the assessment method presented here can be used as initial guidance. Furthermore, there is future opportunity to also consider pre-treatment requirements to achieve beneficial use of the treated water. Recent advances in the development of biological water treatment techniques seem to be promising and a number of these have potential application in treating saline mine water while address some of the shortcomings with traditional approaches.

RO is highly effective in salinity and sulfate removal but also costly. When coupled with RO, the innovative FO approach has great potential of reducing RO costs but more understanding and trials in real coal mine voids are needed to better comprehend the transferability of this methodology. ED and RED showed strong evidence in terms of outperforming RO but have been struggling to maintain high performance and lack satisfactory large-scale examples. Similarly, biodesalination has been shown to be an outstanding candidate to achieve water quality guidelines, but to validate its practical salt removal effectiveness upscaling in the field with mine affected water is required.

In this regard, it is recommended to apply this framework to quantitively compare water treatment technologies according to their category. On the one hand, membrane techniques (RO, ED, RED) can be examined according to types of membrane, treatment arrangements and energy sources. Treatment options under this category are better established and have more large-scale data. Nevertheless, to increase membrane techniques attractiveness in treating residual voids, clear beneficial water re-use needs to exist to compensate for or offset the high investment costs. The major constraint will be securing a cost-effective energy source and the need to provide active inputs and maintenance for mine voids.

On the other hand, biological technologies can be investigated in terms of halotolerant and halophilic microbes comparing different strains, pH, temperature, and initial salinity levels. This category has potential cost-effectiveness and can have visual or other benefits. But even though biological technologies may offer the advantage of lower costs, their salt removal capability need to be demonstrated in saline residual voids. These technologies may provide sufficient results if considered early and proactively used through the life of a mine.

In general, a more detailed literature review combined with thorough secondary or primary data collection would be helpful to draw conclusions and provide robust, science-based, and in-depth technical advice on water treatment for coal mine residual voids. Specific secondary data about water treatment in coal mine residual voids can be scarce and conclusions from primary data collection need to consider scalability issues.

There is a need to incorporate residual void studies earlier in the mine life cycle. Ongoing commitment to treat water across the life of mine is likely to avoid or minimise the need for water treatment and increase the potential benefits of water in mine voids after closure. However, as there are many voids that are highly saline, there is a need to consider how to treat highly saline water already present in many coal mine voids as well as preventing salinisation in new residual voids. Cost-benefit analyses are recommended to investigate the full benefits and early decision implications of having residual voids as post-mining land uses.

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