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Sanciolo, Peter, Haby, Carl, Sharma, Ashok, Muthukumaran, Shobha and Gray, Stephen (2024) Wastewater desalination for irrigation in inland regions. Water Reuse, 14 (4). pp. 626-641. ISSN 2709-6092

Water Reuse

 Water Reuse Vol 14 No 4, 626 doi: 10.2166/wrd.2024.069

Wastewater desalination for irrigation in inland regions

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ABSTRACT

Desalination using membrane processes is increasingly being implemented in coastal regions of the world to meet the water needs of the growing population. The use of this water treatment option to meet the growing water needs in inland regions, however, is impeded by the cost and regulatory challenges associated with responsible disposal of the concentrate brine. For inland regions of Australia, the use of evaporation ponds (EPs) is the only available brine management option. The high cost associated with construction and the high land requirements for EPs necessitates low waste brine volume production. This desktop study investigated the feasibility of achieving very high water recoveries and very low waste brine volumes in the reverse osmosis desalination of municipal wastewater for irrigation of crops near the inland town of Horsham, Victoria, Australia. Interstage lime and soda ash softening was selected as the means of removal of the scalants that prevent the achievement of high water recovery. It is hoped that this study will provide valuable information to aid in the planning of water reclamation operations for agricultural applications in inland areas at a time of increasing demand for water for food production and forecasts of population growth and climate change.

Key words: climate change, evaporation pond, high recovery RO, inland desalination, waste brine management

HIGHLIGHTS

- Wastewater desalination is studied for its high reuse potential in inland regions.
- Treatment process to mitigate high scaling potential in membranes is considered.
- The economic viability of desalination and high recovery in a strict regulatory environment is discussed.

INTRODUCTION

The scarcity of fresh water in the arid and semi-arid inland regions of Australia has long been recognised as a major challenge for farming operations. This scarcity has traditionally been mitigated by the development of surface water diversion to irrigation systems that allow farming in these regions. In the Riverine Plains and Mallee region of the state of Victoria where the town of Horsham is located, the concomitant clearance of deep-rooted native vegetation coupled with irrigation has resulted in more water entering the groundwater system, resulting in the mobilisation of salt to the land surface and to the rivers (Hart *et al.* 2020). Consequently, the primary water quality issue in the Wimmera region where the town of Horsham is located is high salinity due to groundwater intrusion (MDBA, n.d.). The median salinity for the Wimmera River at the Horsham Weir in 2019, for example, was 1,234 μS/cm (MDBA 2020).

Rural water for irrigation in the Horsham region is supplied by local water reservoirs that are supplemented by the Wimmera Mallee Pipeline, which takes its water from Lake Bellfield. Water allocations and entitlements are bought by the Commonwealth Government to manage environmental flows, severely restricting access to irrigation during prolonged dry periods (Government of Victoria 2019).

The stress and uncertainty associated with dryland farming in the region could be alleviated by further treatment of the municipal wastewater to make it more suitable for irrigation. The Horsham municipal wastewater treatment plant (WWTP) treats the sewage by preliminary treatment via screening, primary treatment via sedimentation, and subsequent secondary treatment via activated sludge and clarifiers. It consistently and reliably produces approximately 4 ML/day of treated wastewater. Most of the wastewater is recycled for irrigation in the region, with very small volumes being discharged as wet weather releases into the nearby surface water – the Wimmera River (Coutts 2006). The motivation for use of wastewater for irrigation is, however, largely to avoid having to meet increasingly stringent WWTP effluent discharge standards for surface waters, rather than due to high demand (Radcliffe 2022). Due to the high salinity of the reclaimed water, the demand for reclaimed water is not as high as it could be. The average February electrical conductivity (EC) of the Horsham wastewater at the end of the maturation lagoon between 2016 and 2022 was 1,599 μS/cm with a standard deviation of 133 μS/cm, while the EC of the treated wastewater in storage for the same period was 1,920 μS/cm with a standard deviation of 194 μS/cm (GWMWater website).

The need for lower salinity reclaimed water in the Horsham region is demonstrated by the recent establishment of two small-scale desalination facilities. A Victorian Government funded project to build infrastructure and technology to dramatically reduce salinity and turbidity issues that limit the use of recycled water in Horsham has recently started. This project uses reverse osmosis (RO) to decrease salinity of the WWTP wastewater for use in Agriculture Victoria's SmartFarm for research purposes (The Weekly Advertiser 2021). Brine management in this facility is via evaporation ponds (EPs). Another recent small-scale desalination facility that uses EPs for brine management in the Horsham region is that of Australian Plant Proteins. The State Environmental Protection Authority (EPA) approval has been given for the building of two EPs with a combined volume of approximately 23,300 kL and a land area of approximately 25,000 m^2 to take an average of 57,600 L/day of RO brine over a 10-year period of operation of an Australian Plant Protein facility in Horsham (EPA 2022).

The use of RO to supplement water resources has been widely used in the coastal regions of Australia. The waste brine for the RO is returned to the ocean by these coastal RO facilities. Inland regions such as Horsham, however, are faced with brine management challenges. Discharge to surface waters, groundwater (deep well injection), or land application are highly unlikely to be accepted by regulatory authorities due to the potential of harm to human health or the environment, leaving the use of EPs as the only management option. Due to the high cost of construction and maintenance, the use of EPs for waste RO brine management is only feasible for small volumes in areas with sufficient evaporation potential (Mickley 2008). Furthermore, the evaporation potential decreases with increasing brine salt content (Mickley 2020). The use of thermal evaporators is also a potential option, provided that a small enough volume of waste brine can be achieved.

The average annual pan evaporation for the Horsham region is 1,400–1,800 mm, while the average rainfall is 400–600 mm/year (WCMA 2019]) yielding an effective evaporation potential of 1,000–1,200 mm/year, which may be sufficient for evaporation pond management of waste brine provided that sufficiently high water recoveries can be achieved (Barron *et al.* 2015). These rainfall and evaporation statistics, however, do not account for the predictions of more intense rainfall events due to climate change (Government of Victoria 2020).

Lime and soda ash softening (LS) has been selected in the current study as a means for scale control to increase RO water recovery. Other emerging technologies for high recovery RO (HR RO) exist (Mickley 2020), but they are not as mature as LS and detailed cost information for these technologies is not readily available from manufacturers (Mickley 2008) and from the literature. LS is a widely employed robust technology for the removal of scale precursor ions such as calcium, barium, magnesium, strontium, and silica (Backer *et al.* 2022), and a wealth of detailed literature cost estimates of RO treatment using interstage LS with evaporation pond (EP) is available (Mickley 2008), involving LS treatment of the RO brine and subsequent further RO treatment of the brine to obtain more low-salt product water and decrease the volume of waste brine, followed by subsequent EP management of the resulting brine. The costing in the current study, therefore, needs to be considered as broadly indicative of what could be achieved with LS and EPs as a base case for future comparison with emerging technology when they become more commercially available.

This desktop study investigated the feasibility of wastewater desalination for irrigation in inland regions using RO with interstage LS to produce high-quality irrigation water and a reduced quantity of waste brine for evaporation to a dry salt product using EPs. It uses the regional Victorian town of Horsham as a case study. The expected achievable RO water recovery and waste brine volume production were estimated from the scaling potential of the wastewater, and the cost associated with brine management using EPs was estimated from the expected volume of waste brine. The cost of the RO plant was estimated using the ratio of the RO plant to evaporation pond requirement from the literature, taking into consideration the evaporation potential of the Horsham region and the wastewater quality. The product water cost from the literature HR RO studies was then used to give indicative cost estimates of the permeate–wastewater blends suitable for growing of vegetables with different salt tolerance. The potential economic viability of vegetable farming with desalinated Horsham wastewater in the Horsham area was also assessed. The methodology developed for the feasibility investigation of wastewater desalination for irrigation in the inland regions will help water professionals conduct similar studies in other regions of the globe.

CASE STUDY AREA

The rural Australian city of Horsham (Latitude 36.67°S, Longitude 142.17°E, Altitude 134 m) is located in the inland Victorian Grampians region, approximately 290 km west-northwest of Melbourne, the capital of the state of Victoria, and approximately 170 km from the sea (see Figure 1). It has a cold semi-arid climate with low summer humidity and a wide diurnal temperature variation (ABOM (n,d.)), and has a population of approximately 20,000. The municipal wastewater from the Horsham region and larger regional towns in the Grampians Wimmera Mallee (GWM) region where Horsham is situated is entirely recycled for use in urban areas that have restricted access during irrigation, and for irrigation of pastures and vineyards (Radcliffe 2022). The central region of the Wimmera–Avon basin where Horsham is situated has a very unreliable natural surface water supply that is supplemented with groundwater and regulated irrigation channel water from surface water outside of the region. This region's natural surface water enters terminal lake systems rather than discharging into the state's main river, the Murray River. It has an annual entitlement of 2.3 GL from the Murray River basin (Government of Victoria 2019).

Figure 1 | Case study area, location of the town of Horsham in the state of Victoria (top), irrigation regions in the vicinity of Horsham (bottom).

METHODOLOGY

The feasibility of desalination in the Horsham region was assessed by adapting the approach taken in US studies on inland desalination (Mickley 2008, 2020) to the case study area, namely, (1) the suitability of the region for EPs based on the evaporation potential of the Horsham region, (2) the expected achievable water recovery based on the scaling potential of the WWTP feedwater and primary RO brine after LS, (3) the evaporation pond requirements and costs, based on the estimated achievable water recovery, (4) the interstage LS RO desalination plant requirement and cost based on ratios of desalination plant and evaporation pond requirements from the literature, taking into consideration the Horsham wastewater quality and evaporation potential, and (5) the potential economic viability of vegetable farming with desalinated Horsham wastewater based on the estimated unit cost of desalinated water–wastewater blends, the value of vegetable crops that can be grown in the region, and the expected cost of pipeline irrigation water. A flow diagram of the information inputs from the literature and the calculations used/conducted in this study for capital costs is shown in Figure 2. The literature sourced information used in calculation of cost of RO permeate product water ($/kL), cost of permeate/feedwater blends, and comparison with pipeline water for different crops are shown in Figure 3. The operation and maintenance (O&M) cost estimates were also incorporated in the overall product water cost computations.

Suitability of the region for EPs

Although the use of EPs is the only practicable and feasible brine management option for inland desalination in the Australian context, primarily due to regulatory requirements, the high cost of construction of EPs limits their economic applicability to regions with appropriate combinations of evaporation and rainfall. The assessment of the suitability of the Horsham region for the use of EPs was based on rainfall and evaporation statistics from the local area management authority (WCMA 2019) and on the results of a literature study of the feasibility of desalination application in Australian traditional agriculture (Barron

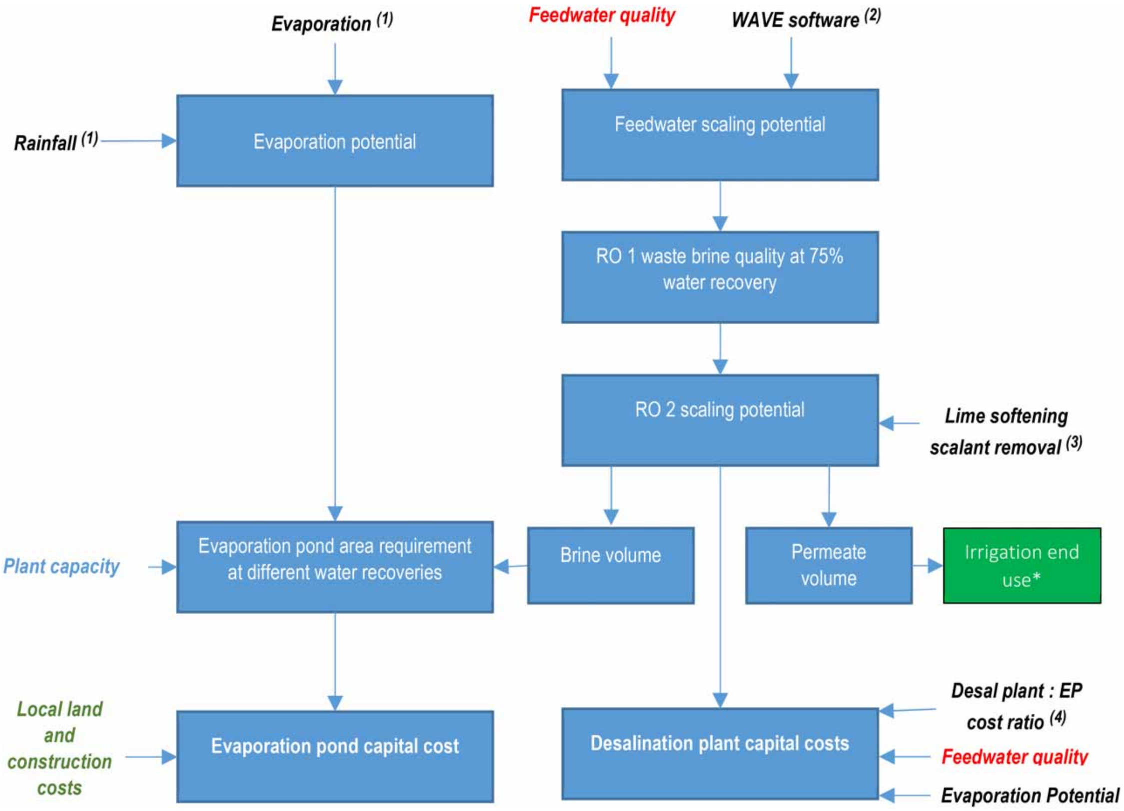

Figure 2 | Flow diagram for calculations of capital cost (in boxes), literature sourced information (in black font), chemical analyses performed for this current study (in red font), locally sourced costs (in green font), setting (in blue font) used for in the study, and * permeate/feedwater blends used for crop irrigation. [(1)] WCMA (2019), [(2)] DuPont (2023a), [(3)] Lu *et al.* (2021), [(4)] Mickley (2008).

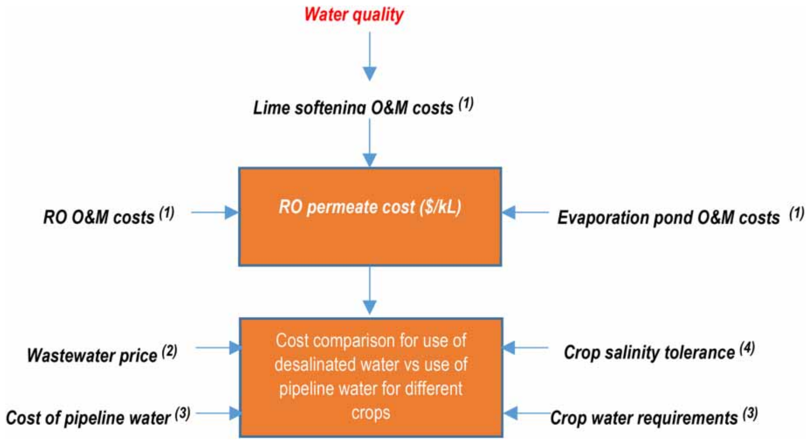

Figure 3 | Literature source (in black font) and chemical analyses (in red font) used in the calculation of cost of RO permeate product water ($/kL), cost of permeate/feedwater blends, and in the comparison with pipeline water for different crops. (1) Mickley (2008), (2) Radcliffe (2022), (3) Top & Ashcroft (2005), (4) NSW DPI (2016).

et al. 2015). These authors proposed an upper water price limit of AU$1.0/kL and performed a Monte Carlo simulation that involved random selection of over 80,000 combinations of desalination and brine disposal costs based on a range of parameters (plant capacity, cost of water production, recovery rate, capital costs of brine disposal, and proportion of plant capacity in cost of water production) to estimate the probability of achieving a water price below this limit at different evaporation potentials. They estimated this probability to be approximately 0.6–0.7 at a water recovery of 90% for the 1,000 mm/year evaporation potential of the Horsham region. The current study investigates the feasibility RO desalination at water recoveries above 90% followed by EP for brine management.

Scaling potential of WWTP wastewater

The scaling potential for the Horsham wastewater was assessed by using the DuPont Water Treatment Design Software (Water Application Value Engine (WAVE)) (DuPont 2023a) to model the scaling potential. This software compares the ionic product for the scalant precursor constituent ions with equilibrium solubility constant at different ionic strengths to determine the level of supersaturation (DuPont 2023b).

The wastewater quality data that were used for this assessment are presented in Table 1 and were obtained by analysis of the Horsham WWTP product water that had been treated with aluminium chlorohydrate coagulant (MEGAPAC 23) in anticipation of the planned use of this coagulant in future dissolved air flotation (DAF) treatment of the wastewater. The modelled feedwater quality after adjustment of pH to decrease calcium and magnesium scaling potential, with charge balance by NaCl, is also presented in Table 1.

Indicative cost estimates of evaporation pond requirements

Indicative cost estimates were made based on the expected brine volume and the evaporation pond cost estimates for the treatment of 1 ML/day of WWTP wastewater. The assumptions and estimates used in the calculations are presented in Table 2.

Estimation of RO with interstage lime softening plant costs for the Horsham region

The indicative costs of a two-stage RO treatment process with interstage LS were estimated from the evaporation pond costs calculated for the Horsham WWTP run at the achievable water recovery based on the scaling potential of desalination with interstage LS (98% overall water recovery). The ratio of RO treatment with LS costs to evaporation pond costs (RO1 + LS + RO2): EP from a literature study with the same treatment scheme and overall water recovery of 98% (Mickley 2008) was used. The evaporation potential of the Horsham area for saline brine (700 mm/year) was compared to the evaporation assumption of the Mickley's (2008) study (1,455 mm/year, 2.96 gpm/acre, Table A2.4, p. 123 Mickley 2008) to estimate the evaporation pond requirement for a hypothetical brine of similar properties to that generated from the Horsham WWTP. The resulting ratios of desalination plant costs to evaporation pond costs (RO1 + LS + RO2): EP are shown in Tables 3 and 4 for capital

Table 1 | Horsham WWTP wastewater quality and WAVE software adjusted parameters used in the DuPont WAVE software modelling, feedwater, and brine pH adjusted to pH 6.0 from native pH of 8.6 and 6.5, respectively, using HCl, lime softened 75% water recovery brine, charge balanced with NaCl.

Parameter	Units	Wastewater	WAVE modelling pH adjusted feedwater (mg/L)
pH		8.6	6.0
Conductivity	μS/cm	1,700	1,518
Ammonia	mg/L	0.1	0.1
Potassium	mg/L	36	36
Sodium	mg/L	230	230
Magnesium	mg/L	18	18
Calcium	mg/L	12	12
Strontium	mg/L	0.11	0.11
Barium	mg/L	0.17	0.17
Carbonate	mg/L	18	0.00
Bicarbonate	mg/L	98	42.9
Nitrate	mg/L	0.04	0.04
Chloride	mg/L	300	364
Fluoride	mg/L	0.6	0.65
Sulphate	mg/L	94	94
Phosphate	mg/L	3	3
Silica	mg/L	0.69	0.69
Boron	mg/L	0.23	0.23

and operation costs, respectively. The volume units used in Mickley (2008) are in mega gallons per day (MG/d), which are finally converted to $/KL in the final cost estimations.

The quality of the Horsham WWTP brine after a first RO stage was compared to a similar brine from this literature study to estimate the relative difference in LS costs. The Horsham WWTP RO brine quality and the literature RO brines are presented in Table 5.

RESULTS AND DISCUSSION

Waste brine management in the Horsham region

The historically available waste brine management practices for advanced water treatment plants have been well documented in the literature (Mickley 2006). These site-specific options have been mainly surface water discharge, deep well injection, land application, and EPs. The available brine management options are, however, very limited for the Horsham region and most inland regions of Australia. Ocean discharge is not available owing to the long distance from the ocean. Discharge to sewers is not advisable due to the adverse effect of salinity on WWTP performance and the increased salinity of any treated wastewater, making the reuse as reclaimed water more difficult. Surface water discharge and land application (rapid infiltration) is not desirable due to salinity and pollution concerns. Deep well injection requires a detailed and expensive characterisation of the underlying aquifers and robust modelling to demonstrate that its use would not impact beneficial uses or other receiving environments. EPs have been identified as the most obvious brine management option for inland regions of Victoria (URS 2010). The cost associated with EP construction and the large land area requirement for EPs, however, are major impediments for this mode of brine management.

Suitability of evaporation ponds for Horsham region

The success of this management option relies on an adequate effective evaporation rate for the location of the pond. For the Horsham region, the average annual pan evaporation is 1,400–1,800 mm, while the average rainfall is 400 to 600 mm/year (WCMA 2019), yielding an effective evaporation potential of 1,000–1,200 mm/year.

Table 2 | Inputs to modelling of evaporation pond costs

Cost item	Value	Reference/comments
Land		
Evaporation Horsham (mm)	1,600	WCMA (2019),
Rainfall in Horsham (mm)	400	WCMA (2019)
Salinity impact factor on evaporation efficiency	0.60	Mickley (2020)[a]
Allowance factor, overflow catchment, high rainfall years	×2	Estimate
Allowance factor for embankments and roads	×1.5	Estimate
Land cost per acre ($/Acre)	3,000	Current value
Earthworks		
Wall height (m)	2.5	Estimate[b]
Shifting cost ($/m^3)	$8	Estimate[b]
Shaping cost ($/m^3)	$3	Estimate[b]
Liner		
Cost ($/m^2)	$15	Estimate[b]
Lay ($/m^2)	$10	Estimate[b]
Access roads		
Cost ($/km)	25,000	Estimate[b]
Drainage		
Cost ($/km)	10,000	Estimate[b]
Fencing		
Fencing ($/m)	$15	Estimate[b]

[a]Based on a 30% reduction due to salinity, plus 10% reduction due to the very high salinity at high water recovery.
[b]Based on indicative quotes.

Table 3 | Estimation of capital cost ratio of desalination to evaporation pond (RO1 + LS + RO2):EP from the literature data for a 1 MG/d feed flow to LS, costs in 2008 USD (Table A2.4 and Table A5.4, Mickley 2008)

	RO and LS costs (RO1 + LS + RO2) ($M)				
Brine	**1st RO stage[b]**	**LS**	**2nd RO stage[a]**	**Evaporation pond costs ($M)**	**(RO1 + LS + RO2): EP ratio**
Mickley (2008), Case 1, Scheme 3 brine	4.4	0.7	2.3	4.2[c]	1.8:1
Hypothetical brine with Horsham quality	4.4	0.7	2.3	8.4[d]	0.9:1

[a]Cost of RO2 for Case 1, $2.5M/MG/d product, Scheme 3 Capital cost, Table A2.4, p.123 (Mickley 2008).
[b]Estimated, based on the ratio of costs of RO1 and RO2 from a literature study of ZLD RO with salt recovery, $6M for RO1 and $3.15M for RO2 (Mickley 2008, Table A5.4, p.156).
[c]With an assumed net *brine* evaporation rate (evaporation minus rainfall) of 2.96 gpm/acre, Table A2.4, p. 123, Mickley (2008), (1455 mm/year).
[d]With a net *brine* evaporation rate (evaporation minus rainfall) of 700 mm/year for the Horsham region, assuming same evaporation to land area relationship as the Mickley's (2008) study costing.

A recent study of the suitability of different inland regions for desalination for agriculture applications, using EPs as a brine management option, ranked the general region around Horsham as borderline between suitable and likely suitable (Barron *et al.* 2015). These authors proposed that Australian farmers are unlikely to pay more than AU$1.0/kL. They estimated that at the Horsham area's pure water evaporation potential of approximately 1,000 mm/year, the probability of product water at this price is low (approximately 0.15). Operating costs were not considered in this study. Although they found that the probability that the product water will cost less than the $1/kL threshold is generally low for the Horsham region, the probability is maximised by operating at high water recoveries due to lower brine volumes and smaller evaporation pond requirements.

Table 4 | Estimation of annual operation and maintenance (O&M) cost ratio of desalination to evaporation pond (RO1 + LS + RO2):EP, $M, 1 MG/d feed flow to LS (i.e., of RO1 concentrate, 365,000 kgal/year)

	RO and LS costs (RO1 + LS + RO2) ($M/year)				
Brine	**1st RO stage[b]**	**LS**	**2nd RO stage[a]**	**Evaporation pond costs ($M)**	**(RO1 + LS + RO2): EP ratio**
Mickley (2008) Case 1, Scheme 3	1.13	0.62	0.365	0.21[d]	10:1
Hypothetical brine with Horsham quality	1.13	0.15[c]	0.365	0.42[e]	4:1

[a]$1.0/kgal (Mickley 2008, Table A5.4, p.156) equating to $0.365M/MG/d/year.
[b]$1.0/kgal, RO1:RO2 feed volume ratio of 2.5:0.8 (3.1:1) (Mickley 2008, Table A5.4, p.156).
[c]Literature Ca and Mg content at 4 times that of the Horsham WWTP brine.
[d]1% of capital cost, with an assumed net evaporation rate (evaporation minus rainfall) of 2.96 gpm/acre (1455 mm/year) (Mickley 2008).
[e]1% of capital costs (Mickley 2008), with a net evaporation (evaporation minus rainfall) rate of 700 mm/year for the Horsham region.

Table 5 | Wastewater composition, expected Horsham brine composition and salinity at 75% water recovery, and compositions of a similar brine (case 1) from Mickley 2008

	Horsham WWTP wastewater composition (mg/L)	**Expected Horsham RO1 brine composition, 75% RO water recovery (mg/L)**	**Case 1 low salinity low flow brine from Mickley *et al.* (2008) (mg/L)**
Na	230	920	613
Ca	12	48	365
Mg	18	72	178
Ba	0.17	0.28	a
K	36	144	32
SO_4	94	376	1,782
Cl	300	1200	555
HCO_3	98	392	464
Si (as SiO_2)	0.69	2.8	11
TDS	1,100	4,400	4,000

[a]The Ba concentration was not modelled in the Mickley 2008 study. This study took a broad approach that focuses on the effect of salinity and the major sparingly soluble salts (Ca and Mg carbonates and sulphates) and silica, and recommends detailed water quality analyses for more accurate estimate of costs.

Commercially ready RO technology for desalination

The HR RO process is defined here as a technology that gives greater than 90% of water recovery. HR desalination is increasingly being practised for many inland industrial applications such as mining wastewater, cooling towers blowdown, and produced water from oil and gas operations. The HR process is cost-intensive and is generally economically feasible when it is part of a process that produces a product of high monetary value. As a result of the high cost, the market for HR RO processing is almost exclusively industrial. The application of HR RO to municipal desalination is limited. There is, however, growing interest in achieving higher recovery levels in the municipal sector (Mickley 2020). Higher recovery processing can result in more efficient use of water resources, reduction of the volume of waste brine for disposal, and, if the achievable water recovery is sufficiently high, provide the opportunity to achieve minimal liquid discharge (MLD) or zero liquid discharge (ZLD) in circumstances where no other disposal options are available.

A strategy that is often used in ZLD and MLD studies is to start with conventional RO to treat the feedwater up to the water recovery just below where scaling begins to occur, then treat the resulting brine to remove the scale precursor chemical constituents using processes such as LS, pellet softening, or ion exchange, putting the resulting treated brine through a secondary RO treatment that will accommodate the higher osmotic pressure, and finally evaporating the remaining water from the brine via thermal processes and/or EPs (Mickley 2008). A diagrammatic representation that is based on this strategy for production of water for crop irrigation is shown in Figure 4. The primary and secondary RO stages in this example are run at 75 and 80%, respectively, but the achievable RO water recovery depends on the scaling potential of the wastewater. The salinity tolerance

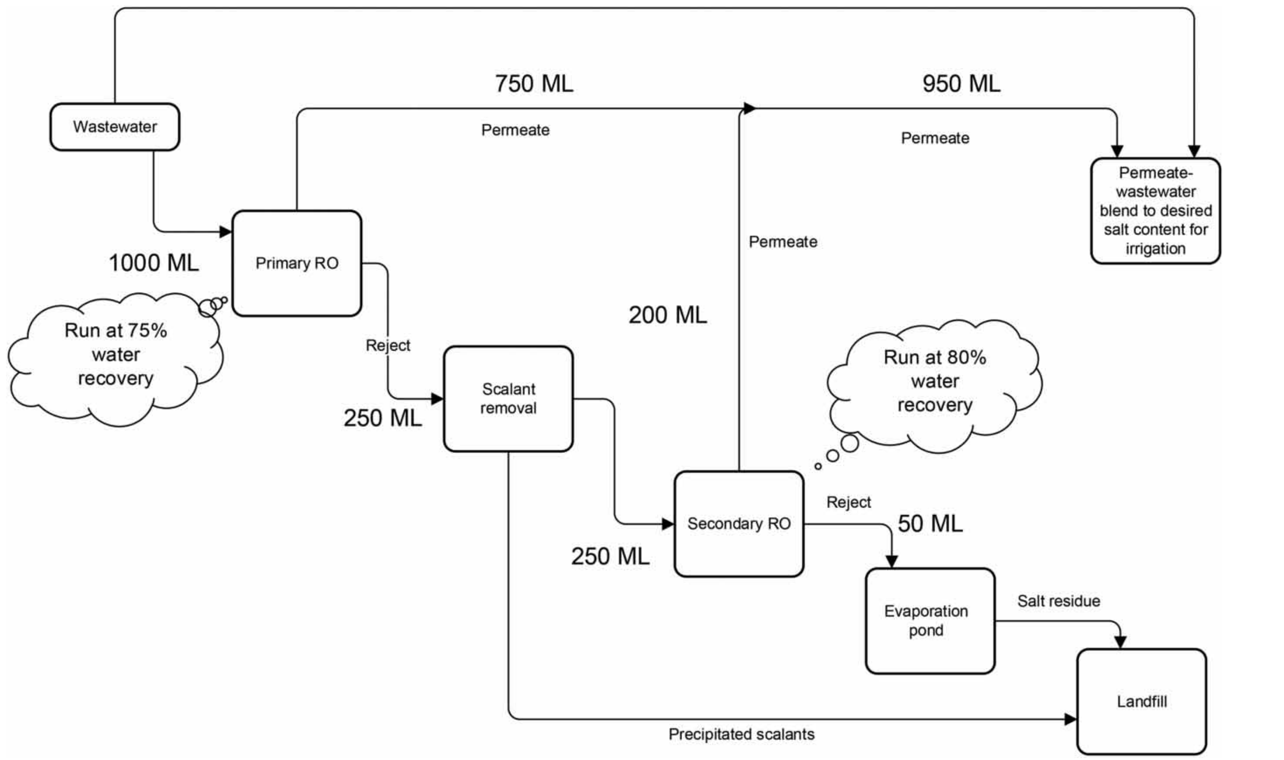

Figure 4 | A high recovery process scheme for production of water for crop irrigation. The RO water recoveries that are shown are examples.

of the crop to be irrigated as well as the soil type of the irrigated land (NSW DPI 2016) determine the blend ratio of permeate and untreated wastewater. In Figure 4, an example of 100 mL of wastewater generation is considered.

Recent emerging technology developments allow replacement of the primary and/or the secondary RO and scalant removal by HR RO processes that take advantage of the induction time (delay) required for scale to form (e.g., closed circuit RO (CCRO)), or use RO technology that will tolerate the formation of scale compounds (e.g., vibratory shear enhanced processing (VSEP), slurry precipitation and recycle RO (SPARRO)) to achieve high water recovery. High pressure membrane systems can be used in the secondary RO stage to overcome pressure limitations at very high water recoveries. Energy requirements due to high osmotic pressures can be minimised by using osmotically assisted RO (OARO) (Mickley 2020). These have been described as emerging technologies and there currently are both short-term and long-term risks associated with these technologies as they have a limited record of reliability and performance (Mickley 2020). The current study, therefore, considers application of some of the more conventional and commercially available technology studied and costed in a 2008 survey of HR and ZLD technologies for water utilities (Mickley 2008) and outlined in Figure 4 for production of irrigation water for the Horsham region.

The highest energy expenditure occurs at the evaporation stage at the tail end of the ZLD or MLD process so the economic viability of the process largely depends on achieving the highest possible water recovery before evaporation is employed (Charisiadis 2018). A lower brine volume entering the evaporation stage equates to lower evaporation pond area requirement.

The combined use of a thermal brine concentrator and EPs has been found to lead to lower brine treatment capital costs than the use of EPs alone, largely due to the lower evaporation pond requirement when using a thermal evaporator. The operation costs and greenhouse gas emissions, however, are higher with the combined use of thermal brine concentrator and EPs than when using EPs alone, largely due to the energy expenditure associated with the use of thermal brine concentrators. The highest capital cost and operating costs of any single brine treatment process step were related to the EPs and the softening stages, respectively (Mickley 2008). The current study will not deal with thermal brine concentrators due to the high cost and energy requirements.

Scaling potential of Horsham wastewater

The scaling potential of the concentrate at different system water recoveries as calculated by the DuPont Water Application Value Engine (WAVE) modelling software are shown in Table 6.

Table 6 | WAVE software modelling of scaling potential of the Horsham wastewater at different RO water recoveries

	Adjusted feed	Overall water recovery (%) 75	80	85	90	92.5	95	96	97	98	99
pH	6.0	6.5	6.5	6.6	6.7	6.8	6.9	6.9	7.0	7.0	7.0
Langelier Saturation Index	−2.89	−1.29	−1.04	−0.71	−0.27	0.04	0.44	0.65	0.89	1.17	1.72
Stiff & Davis Stability index	−2.42	−1.33	−1.16	−0.94	−0.65	−0.45	−0.20	−0.08	0.06	0.20	0.63
Ionic strength (Molal)	802.7	3,171	3,957	5,267	7,864	10,448	15,524	19,228	25,188	36,068	63,132
TDS (mg/L)	0.02	0.06	0.07	0.10	0.15	0.20	0.30	0.37	0.48	0.70	1.26
HCO_3 (mg/L)	42.96	160.9	199.1	261.8	383.1	500.1	718.2	865.0	1,077	1,410	2,209
CO_2 (mg/L)	53.23	55.21	55.82	56.80	58.66	60.51	64.19	66.99	71.59	80.19	115.1
CO_3 (mg/L)	0.00	0.08	0.13	0.23	0.57	1.08	2.67	4.35	7.94	15.93	36.11
$CaSO_4$ (% saturation)	0.24	2.2	3.1	4.5	7.6	10.9	17.8	23.1	32.6	53.0	124.6
$BaSO_4$ (% saturation)	459.5	3,030	3,963	5,553	8,790	12,101	18,864	24,072	33,127	52,330	116,631
$SrSO_4$ (% saturation)	0.20	1.0	1.3	1.8	2.8	3.8	5.9	7.5	10.5	17.3	43.6
CaF_2 (% saturation)	0.66	18.7	32.9	68.7	195.9	415.8	1,204	2,159	4,587	12,934	69,466
SiO_2 (% saturation)	0.49	2.1	2.6	3.5	5.3	7.1	10.7	13.3	17.7	25.9	49.2
$Mg(OH)_2$ (% saturation)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02

The feedwater was found to be supersaturated with respect to $BaSO_4$. In most natural waters, barium is present at a level that would cause barium sulphate precipitation in the concentrate stream. The critical feed concentration of barium may be as low as <15 μg/L in seawaters, <5 μg/L in brackish waters such as secondary municipal wastewaters, or even <2 μg/L if sulphuric acid is added to the brackish waters (DuPont 2023b).

The WAVE modelling indicates that the Horsham RO concentrate becomes supersaturated with respect to CaF_2 at water recoveries between 85 and 90% (see Table 6). The brine becomes supersaturated with respect to $CaSO_4$ at a water recovery between 98 and 99%. The primary RO brine remained undersaturated with respect to $SrSO_4$, SiO_2, and $Mg(OH)_2$ at all water recoveries. Despite the adjustment of the feed pH to 6.0, the Langelier saturation index and the Stiff and Davis Stability indices became positive at a water recovery of approximately 92.5 and 96%, respectively, indicating the tendency to form $CaCO_3$ scale at these water recoveries and above.

Antiscalants can be used to extend the water recovery range. These are commonly available proprietary formulations whose prime active ingredient complexes with the surface of scale crystals, thereby slowing or preventing their further growth and precipitation. The selection and required dosing rate of the antiscalant depends on the scalant species, degree of supersaturation, operating temperature, salinity of the feed, and the membrane type. The supersaturation threshold of the Horsham wastewater above which precipitation is predicted with the use of antiscalants is presented in Table 7. The general capability of the antiscalant to limit $BaSO_4$ scale formation, with ion exchange pre-treatment, has been estimated at 51

Table 7 | Approximate scaling supersaturation thresholds for the Horsham wastewater without interstage softening, pH adjusted to 6.0 with HCl

Scalant	Maximum safe supersaturation with antiscalant (Ning *et al.* 2009)	Water recovery supersaturation threshold (%) No antiscalant	With antiscalant
$CaCO_3$	*LSI: 3.2, **S&DSI: 4.5	Not reached	Not reached
$CaSO_4$	400 × Saturation	Not reached	Not reached
$BaSO_4$	51 × Saturation	Exceeded	80–85
CaF_2	16,000 × Saturation	Not reached	Not reached

*LSI - Langelier Saturation Index
**S&DSI - Stiff and Davis Saturation Index

times the saturation concentration (Ning *et al.* 2009). In the presence of antiscalants, $BaSO_4$ does not precipitate until its concentration exceeds 51× the saturation concentration, i.e., 5,100%. The modelling data in Table 6 indicates that this level of supersaturation is reached at water recoveries greater than 80–85%, requiring mitigation of barium sulphate scaling if this water recovery is exceeded. The amount of scale is low and the scale formation rate with barium or with fluoride salts is typically very slow because of the low concentrations involved (DuPont 2023b) making timely detection of scale formation difficult. If not detected in time, barium sulphate (barite) scale may age into a hard adherent layer, and cleaning may not then be effective and membrane elements may have to be replaced (Boerlage *et al.* 1999, 2002).

Although LS is primarily used for calcium and magnesium removal, it also significantly reduces silica, barium, strontium, and organic substances. Calcium and barium removals of 99% have been reported in laboratory softening trials on coal wastewater (Lu *et al.* 2021). The scaling potential of a brine from RO treatment of the WWTP wastewater at 75% water recovery, that has undergone LS with an estimated 98% Ca, Mg, and Ba removal, is shown in Table 8. Comparison of Table 8 with the literature (Ning *et al.* 2009) on maximum safe supersaturation in the presence of an antiscalant presented in Table 7 reveals that softening is expected to lower the $BaSO_4$ scaling potential to a level that can be tolerated with the use of antiscalants. Due to the relatively low salinity of the feedwater, the pressure required to treat the high recoveries is not a limiting factor. The WAVE software predicts a pressure of 2,200 kPa would be required to achieve 92% water recovery at the RO2 stage from the 75% water recovery RO1 brine, giving an overall recovery of 98%.

Indicative cost of RO using interstage lime softening and EPs for the Horsham region

Costs of EPs

The land and construction costs of an evaporation pond to accommodate the brine from a 1000 m^3/d plant operating at water recoveries between 95 and 99% are presented in Table 9. The local water authority (personal communication) was consulted regarding the expected costs of different components of the pond construction. The supplied data were used to calculate the evaporation costs at different water recoveries. The results are presented in Table 9. The total costs broadly agree with those found in the literature. The total cost of evaporation pond construction with a double synthetic liner and monitoring system has been estimated at between \$0.1M and \$0.2M per acre (in 2007) (Bond & Veerapaneni 2003), equating to AU\$0.0.54M

Table 8 | Wave modelling of scaling potential of lime softened RO1 concentrate generated at 75% water recovery, at different RO2 water recoveries

		RO2 water recovery (%)								
		60	64	68	72	76	80	84	88	92
		Overall water recovery (%)[a]								
	Adjusted feed	90	91	92	93	94	95	96	97	98
pH	6.0	6.3	6.3	6.4	6.4	6.4	6.5	6.5	6.6	6.7
Langelier saturation index	−3.46	−2.41	−2.30	−2.16	−2.02	−1.85	−1.65	−1.42	−1.12	−0.73
Stiff & Davis stability index	−3.47	−2.76	−2.69	−2.60	−2.51	−2.40	−2.27	−2.12	−1.93	−1.69
Ionic strength (Molal)	3,240	8,026	8,911	10,015	11,426	13,313	15,937	19,835	26,238	38,578
TDS (mg/L)	0.06	0.14	0.15	0.17	0.20	0.23	0.28	0.34	0.46	0.67
HCO_3 (mg/L)	161.3	388.7	430.3	481.8	547.3	634.3	754.0	929.1	1,209	1,715
CO_2 (mg/L)	165.4	171.4	172.6	174.0	175.8	178.1	181.0	184.8	189.7	194.1
CO3 (mg/L	0.03	0.19	0.25	0.33	0.45	0.64	1.00	1.73	3.58	9.57
$CaSO_4$ (% saturation)	0.05	0.16	0.18	0.21	0.25	0.30	0.38	0.49	0.69	1.1
$BaSO_4$ (% saturation)	66.0	193.2	217.4	247.7	286.9	340.0	414.9	529.0	724.4	1,136
$SrSO_4$ (% saturation)	0.02	0.07	0.08	0.09	0.10	0.12	0.14	0.18	0.25	0.41
CaF_2 (% saturation)	0.38	4.0	5.3	7.2	10.2	15.3	24.7	44.4	95.0	276.4
SiO_2 (% saturation)	1.9	5.0	5.6	6.3	7.2	8.4	10.2	12.8	17.1	25.8
$Mg(OH)_2$ (% saturation)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a]Overall water recovery = 75 + (25 × RO2 WR)/100

Table 9 | The land and construction costs of an evaporation pond, 1ML/day (1000 m^3/d) feed flow rate

	Overall water recovery (%)					
Cost item	**75**	**95**	**96**	**97**	**98**	**99**
Land requirement (acres)	376	19	15	11	8	4
Land ($)	$1,127,657	$56,383	$45,106	$33,830	$22,553	$11,277
Earthworks	$41,822,917	$2,091,146	$1,672,917	$1,254,688	$836,458	$418,229
Liners	$38,329,138	$1,969,981	$1,582,494	$1,194,025	$804,018	$411,039
Access roads	$616,610	$137,878	$123,322	$106,800	$87,202	$61,661
Drainage	$246,644	$55,151	$49,329	$42,720	$34,881	$24,664
Fencing	$73,993	$16,545	$14,799	$12,816	$10,464	$7,399
Total ($)	**$82,216,960**	**$4,327,084**	**$3,487,967**	**$2,644,878**	**$1,795,576**	**$934,269**
Total (M$/hectare)	$0.54	$0.57	$0.57	$0.58	$0.59	$0.61
Total (M$/acre)[a]	$0.22	$0.23	$0.23	$0.23	$0.24	$0.25

[a]Assumed land cost of $3,000/acre.

to AU$1.1M per hectare (1 USD in 2007 = 1.47 USD in 2023, 2023 USD to AUD exchange rate = 1.50, 03-07-23 (CPI Calculator 2023a, Wise.com website). The data in Table 9 highlight that the use of EPs at a typical water recovery of 75% for RO without interstage lime softening is prohibitively expensive. The capital cost of an RO plant without interstage lime treatment operating at this typical water recovery of 75% has been estimated to be $2.5M/MG/d of product (Mickley 2008), equating to AU$1.47/ML product or AU$1.96/ML feed flow rate. The management of the waste brine from this plant would require an evaporation pond with a capital cost of over $82M. Increasing the water recovery to 98% by using interstage lime softening would bring the evaporation pond capital cost to approximately that of the cost of the RO plant ($1.8M).

Cost of RO treatment with interstage lime softening

The capital and annual O&M cost ratios of desalination with interstage LS to evaporation pond (RO1 + LS + RO2):EP from the literature (Mickley 2008) were used to estimate the corresponding costs of RO with interstage treatment for the Horsham region at 98% water recovery, taking into account the different evaporation rates of the Horsham region, and the different scalant ion concentrations (Ca, Mg and Ba) of the Horsham wastewater (see Section 2.5). The results are presented in Table 10.

The difference in evaporation potential between the literature study and the current study had a major effect on the (RO1 + LS + RO2):EP ratio. The literature ratio was found to be approximately 2:1. The capital costs of RO with interstage LS were approximately double the EP capital cost, largely due to high brine evaporation potential (1,451 mm/year: 2.96 gpm/acre) (Table A2.4, p. 123 (Mickley 2008)) and concomitantly low EP costs in these cost estimates. The lower brine evaporation potential of the Horsham region (assumed to be 70% of the water evaporation rate, i.e., 700 mm/year), however, doubles the EP capital costs, bringing the ratio closer to 1:1. The lower scalant ion concentration in the Horsham wastewater decreased the O&M cost of LS but did not change the capital costs.

Another difference between the literature study and the current study that may influence the (RO1 + LS + RO2):EP ratio is the concentration of calcium and magnesium in the feed and the RO1 brine. The RO1 brine total concentration of calcium and magnesium in the current study is considerably lower than that of the Mickley *et al.* literature study (see Table 5),

Table 10 | Cost of interstage RO treatment, 98% water recovery

	(RO1 + LS + RO2) : EP ratio		
Cost type	**Literature[a]**	**Horsham estimate**	**Interstage RO desalination plant**
Capital	1.8:1	0.9:1	$1,616,018
Annual O&M	10:1	4:1	$71,823[b]

[a]As estimated in Tables 3 and 4, based on Mickley (2008).
[b]Assuming evaporation pond O&M of 1% of evaporation pond capital costs (i.e. Interstage RO O&M cost = 4 × 0.01 × 1,795,576).

indicating that the LS treatment cost required for removal of these constituents in the current study would be less than for the literature study.

Unit cost of blended water for crop irrigation

This costing is based on the Mickley (2008) water unit cost estimates for desalinated water produced from a feedwater with similar salinity but higher calcium and magnesium concentrations (see Table 3). This costing is, therefore, a conservative estimate as the LS costs associated with the Horsham wastewater are likely to be less than those of the Mickley (2008) study. The O&M unit costs of the desalinated water in this literature study were estimated to be 3.0 US$/kgal (2008), equating to AU $1.69/kL (2023) (1 USD in 2007 = 1.47 USD in 2023, 2023 USD to AUD exchange rate = 1.50, 03-07-23 (CPI Calculator 2023a, Wise.com website)).

Many recycled water schemes involving reuse of treated sewage effluent for agricultural and municipal irrigation have provided water free of charge or for a nominal fee as this provides a secure means of disposing of the effluent rather than to achieve an economic return (WSAA 2005). The GWMWater reclaimed water scheme, for example, was built in 1995 and sold effluent to wine grape growers for AU$ 0.205/kL, resulting in operating costs to GMWWater being substantially lower than its previous self-operated land disposal system (Radcliffe 2022). Reclaimed water prices up to $0.3/kL, and between $0.3/kL and $0.6/kL, have been rated as 'good' and 'possible' for irrigation of grape vines (Arris 2009). The estimated cost of blends of permeate and non-desalinated wastewater for a wastewater with the salinity of the analysed wastewater (TDS 1,100 mg/L) and a permeate salinity of 100 mg/L are presented in Table 11. These costings use a nominal wastewater price of $0.43/kL, derived from the 1995 price charged to wine grape growers (Radcliffe 2022) using a cumulative inflation rate of 210% for the 1995–2023 period (CPI Calculator 2023b). This price was used as it is what could be recovered for the sale of the wastewater without desalination.

In 2013, it was estimated that Australian farmers were unlikely to pay more than AU$ 1.2/kL (Barron *et al.* 2015), equating to AU$1.56 in 2023 (with an average inflation rate of 2.6). This suggests that most of the blends outlined in Table 11 may be attractive water resources for farmers in the Horsham region, particularly as they could provide reliable supply and the salinity of the irrigation water can be tailored to grow high-value crops such as vegetables. The generation and use of these permeate–wastewater blends would also be of great benefit to the water authority at it would increase demand for the wastewater, thereby decreasing the need to discharge to the local river at times of surplus and meet increasingly stringent WWTP effluent discharge standards for surface waters.

The salt tolerance levels of vegetables (NSW DPI 2016) in the Horsham region, which has moderate permeability soils (Agriculture Victoria), are shown in Table 12.

The likely cost of desalinated water blend for irrigation with no decrease in crop yield for different crop yields is presented in Table 13 and is compared to the expected non-fixed, i.e., total variable costs, associated with the use of water that is delivered via the current pipeline infrastructure (Top & Ashcroft 2005).

The comparison in Table 13 shows that, assuming a wastewater (reclaimed water) price of $0.43/kL ($0.205/kL in 1995 (Radcliffe 2022)), the desalinated water cost estimates for the permeate–wastewater blends are considerably lower than the expected total variable cost associated with use of pipeline water for these high water demand crops, allowing room for inclusion of other site-specific costs such as pumping, reticulation, and storage costs for the desalinated water blend that have not been included in the current study.

Table 11 | Cost, EC, and TDS of blended water, feedwater TDS: 1,100 mg/L, RO permeate TDS: 110 mg/L

		Permeate to feedwater blend									
Permeate	0	1	2	3	4	5	6	7	8	9	10
Feed	10	9	8	7	6	5	4	3	2	1	0
EC (mS/cm)	1.72	1.56	1.41	1.25	1.09	0.94	0.78	0.63	0.47	0.31	0.16
TDS (mg/L)	1100	1000	900	800	700	600	500	400	300	200	100
		Cost of blended water ($/kL)									
	0.43	0.56	0.68	0.81	0.93	1.06	1.19	1.31	1.44	1.56	1.69

Table 12 | Crop salinity tolerance to EC (mS/cm) in irrigation water, yield reductions for irrigation with saline water in moderate-to-slow draining soils. (NSW DPI 2016)

Crop	No reduction	10% reduction	25% reduction
Broccoli	1.8	2.6	3.7
Tomato	1.5	1.9	2.4
Potato	1.1	1.7	2.5
Capsicum	1.0	1.5	2.2
Lettuce	0.9	1.4	2.1
Onion	0.8	1.2	1.8
Carrot	0.7	1.1	1.8

Table 13 | Comparison of cost of desalinated water blends with, yields, water usage, and total variable costs

Crop	Marketable yield[a]	Water application rate[a] (ML)	Total variable cost[a] ($)	EC requirement for no decrease in yield (mS/cm)	Required permeate to wastewater blend ratio	Cost of water blend ($/ML)	Cost of desalinated water blends ($)
Carrot (kg)	46,258	6	10,345	0.7	7:3	1,310	7,860
Lettuce (kg)	32.100	4	10,989	0.9	3:2	1,190	4,760
Capsicum (kg)	57,838	6	54,688	1.0	1:1	1,060	6,300
Tomatoes (Fresh-carton)	6,000	8	45,831	1.5	1:4	680	5,440
Broccoli (kg)	8,051	5	9,788	1.8	[b]	430	2,150

[a]TOP & Ashcroft (2005).
[b]Blending and desalination not required for this crop.

These estimates are broadly indicative as they are based on broad assumptions and require consideration of other site- and crop-specific costs and prices setting for a more accurate costing to be developed. They, however, warrant a more detailed and accurate assessment of the economic viability of farming with desalinated wastewater in the Horsham region. They suggest that the use of fit-for-purpose desalinated reclaimed water blends in the Horsham region may allow high-value crop farming that has not been possible in the past due to the high water demand of these crops. The economic benefit of such farming to the Horsham region and other semi-arid regions of Australia could be considerable, particularly at times of drought when access to irrigation is severely limited. The reliable supply of fit-for-purpose reclaimed water blends from WWTPs offers the opportunity to mitigate some of the severe economic and social challenges faced by rural and regional towns in semi-arid regions during droughts. Another benefit of the use of fit-for-purpose desalinated reclaimed water blends would be that farmers that currently use pipeline water could be encouraged to switch to reclaimed water blends, thereby freeing up some of the demand for pipeline water, which is a limited and expensive resource. The lower demand for pipeline water would allow better management of precious surface water resources in the region at a time of increasing demand for water for food production and forecasts of dwindling water resources due to population growth and climate change.

CONCLUSIONS

The land in the vicinity of Horsham is semi-arid and suffers from irrigation water shortages in prolonged dry periods. This shortage could be reliably overcome by the use of the some or all of the approximately 4 ML/day of WWTP municipal wastewater for irrigation. This potentially valuable and reliable resource is currently underutilised owing to its salt content. This study aimed to investigate the feasibility of desalination of the Horsham wastewater for agricultural applications. It showed that the wastewater has a high potential for $BaSO_4$ scaling, limiting the expected RO water recovery to approximately 75%. Without further brine treatment the evaporation pond requirement from a 1 ML/day feed flow rate RO plant with a capital cost of approximately $1.8 M run at this water recovery is expected to have a capital cost of over $82 M. The study, however, showed that high water recoveries and low waste brine volumes can potentially be achieved for this WWTP wastewater by treating the brine to remove scalants and subsequently further recovering water from the brine by RO treatment, thereby dramatically decreasing the volume of the waste brine and evaporation pond capital cost. Using this brine treatment, a water recovery of 98% is expected to be achieved, thereby bringing the evaporation pond capital cost to approximately that of the RO plant.

The cost for a 1 ML/day feed flow desalination plant, including EPs, is expected to be of the order of M$3.4, with annual operating and maintenance costs of the order of AU$0.1M. The permeate unit cost was estimated to be of AU$1.7/kL. Assuming an untreated wastewater price charged to farmers of AU$0.4/kL, permeate blends with different salinity content (EC) between 0.16 and 1.7 mS/cm were estimated to cost between AU$0.4/kL to 1.7AU$/kL. Consideration of the water quality and quantity needs and value of different crops, the cost associated with the use of currently available irrigation water, and the expected cost and salinity of desalinated water blends revealed that these desalinated blends may offer the opportunity to economically grow vegetable crops under circumstances where farming operations would not be feasible or be of too high a risk due to the potential of pipeline water shortages and the concomitant increase of pipeline water prices. A more detailed and accurate assessment of the economic viability of farming with fit-for-purpose desalinated reclaimed water in the Horsham region is warranted. The methodology presented in this publication can be adopted by water professionals across the globe to investigate similar wastewater reuse opportunities to provide alternative water supply for irrigation and meet safe wastewater disposal regulatory requirements.

ACKNOWLEDGEMENTS

The authors would like to acknowledge that this research project was jointly funded through the Australian Government's Future Drought Fund and Grampians Wimmera Mallee Water.

ETHICS STATEMENT

No human participation or animal testing was involved in the research.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 18 July 2024; accepted in revised form 28 September 2024. Available online 24 October 2024