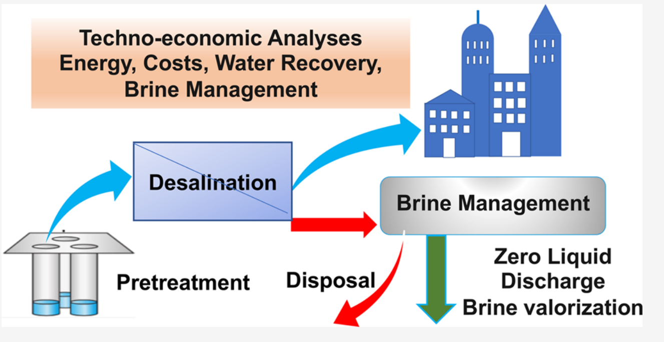
ACS ES&T Engineering

pubs.acs.org/estengg Review

Analysis of Brackish Water Desalination for Municipal Uses: Case Studies on Challenges and Opportunities

Xuesong Xu, J. Erik Ness, Ariel Miara, Kurban A. Sitterley, Michael Talmadge, Barbara O'Neill, Katie Coughlin, Sertac Akar, E. M. N. Thiloka Edirisooriya, Parthiv Kurup, Nalini Rao, Jordan Macknick, Jennifer R. Stokes-Draut, and Pei Xu*

Cite This: https://doi.org/10.1021/acsestengg.1c00326 Read Online



ABSTRACT: Brackish water is a widely available, nontraditional water resource that can augment limited freshwater supplies. Although brackish water desalination has been continuously implemented in the United States and worldwide, it is necessary to reduce further its energy consumption, costs, and environmental impacts. This study conducted technoeconomic analyses to evaluate the current desalination and brine management technologies, focusing on the key factors and opportunities for sustainable brackish water desalination for municipal uses. Three case studies were selected as baseline representative of different geographic and operational conditions, including water quality, plant size, pretreatment, desalination, and concentrate management. The technoeconomic analyses and model simulations identified challenges, opportunities, and research priorities to achieve specific pathways for enhanced brackish water desalination regarding levelized costs of water, electricity intensity, water recovery, zero liquid discharge, and brine valorization.

KEYWORDS: *brackish water, desalination, municipal uses, brine management, technoeconomic assessment*

1. INTRODUCTION

A sustainable water supply from all available water resources is essential to economic development, ecological health, and human wellness. Traditional freshwater supplies in most regions are unsustainable due to overwithdrawing[1−3] and deteriorating water quality by pollution.[4,5] The development of nontraditional water sources, such as seawater, brackish water, and wastewater, is critical to augment or replace diminishing freshwater supplies for various sectors. Brackish water is a widely available but largely untapped resource for many of the increasingly water-stressed regions in the U.S. and worldwide. Advances in desalination technologies provide an opportunity to utilize nontraditional waters to meet growing water needs. As the cost of desalinated water decreases due to technological advances and the cost of traditional water sources increases, it is expected that desalination capacity will continuously expand.[6,7] Foundational data need to be synthesized and standardized methods established to evaluate the technical performance, benefits, and costs of technology innovations to develop sustainable, reliable, and resilient desalination technologies.[8]

This study critically reviewed the state-of-the-art desalination technologies, including key factors, challenges, and opportunities for brackish water supplies to be viable compared to other traditional water sources. A new decision-support tool—the Water Technoeconomic Assessment Pipe-Parity Platform (WaterTAP3) developed by the National Alliance for Water Innovation (NAWI)—was used to analyze the technoeconomic aspects of brackish water desalination. Three case studies were selected to represent a broad range of desalination technologies and brine management options based on data collected from literature review, technical reports, and interviews with engineers and water agencies operating such facilities. The water quality, system performance, capital investment, operation and maintenance (O&M) costs, levelized cost of water (LCOW), energy intensity, and cost of waste and residual management were simulated using the WaterTAP3 model. The opportunities and research needed to improve brackish water desalination sustainability were discussed. The study also aimed at increasing industry awareness and understanding of current desalination technologies and future prospects to inform decision-making.

Special Issue: Technology Baselines and Innovation Priorities for Water Treatment and Supply

Received: September 9, 2021
Revised: February 4, 2022
Accepted: February 4, 2022

1.1. Characteristics of Brackish Source Water. In this study, brackish water for the municipal sector is defined as a nontraditional water source having total dissolved solids (TDS) concentrations from 500 to 10,000 mg/L. The lower bound on TDS was extended to 500 mg/L in this study based on the U.S. Environmental Protection Agency (USEPA) Secondary Maximum Contaminant Level (MCL), above which the water is generally considered unpalatable for human consumption. Other chemical contaminants (e.g., arsenic, nitrate, selenium, uranium, radium, heavy metals, chlorinated and fluorinated organic contaminants, and other contaminants of emerging concern), if present, would also need to be reduced to water quality standards for specific uses during desalination or specialized treatment.

In 2017, the U.S. Geological Survey (USGS) completed a national brackish groundwater assessment with a database including distribution, chemical characteristics, and aquifer information.[9] According to the USGS assessment, 20% of groundwater in the U.S. is considered brackish, with TDS levels ranging from 1,000 to 10,000 mg/L. Brackish groundwater has been identified in all states, except New Hampshire and Rhode Island, with the most extensive band observed in the central regions from Montana and North Dakota to Texas and Louisiana. The groundwater salinity typically increases with the aquifer depth in these regions. In general, groundwater salinity increases from being slightly saline with TDS of 1,000 to 3,000 mg/L at 500 ft (152 m) below land surface, to more saline with TDS of 3,000 to 10,000 mg/L by 1,500 ft (457 m) below land surface, to exceeding 10,000 mg/L by 3,000 ft (914 m) below land surface.[9]

Regarding the specific inorganic constituents in brackish groundwater, calcium sulfate and silica have a significant presence inland relative to coastal areas, while sodium chloride can be found in landlocked areas but is more prevalent in coastal areas due to seawater intrusion. The USGS data show that chloride and bicarbonate are likely dominant in relatively low-TDS samples.[10] Some brackish water can contain sparingly soluble minerals such as calcite ($CaCO_3$), barite ($BaSO_4$), gypsum ($CaSO_4$), or chalcedony (SiO_2), which could cause problems by mineral precipitation and scaling and impede transportation, storage, uses, and treatment of brackish water.

The chemical composition and TDS of source water determine the costs and selection of treatment technologies. The geochemical characteristics of groundwater vary depending on the geologic formation and interactions with hydrologic and geochemical processes and may contain certain constituents that need to be removed for safe water uses.[9] About 5−7% of the sampled domestic wells had arsenic, nitrate, manganese, strontium, and gross alpha-particle radioactivity present at levels exceeding the USEPA MCLs for public water supplies or the USGS Health-Based Screening Levels (HBSLs). Boron, fluoride, uranium, and gross beta-particle radioactivity were present at levels greater than MCLs or HBSLs in about 1−2% of the sampled wells. Iron and manganese concentrations were higher than the secondary MCLs in about 19−21% of wells.[9] In addition, groundwater may be contaminated by synthetic organic contaminants,[11,12] such as perfluoroalkyl and polyfluoroalkyl substances, pesticides, chlorinated solvents, and volatile organic compounds, which can cause potential risks for human health and need to be removed prior to use.

1.2. Current and Potential Uses of Brackish Water. The USGS National Water-Quality Assessment Program reported that 15% of domestic wells (private wells used for household drinking water) had TDS concentrations greater than 500 mg/L.[9] Approximately 91% of the brackish water samples contain 500−3,000 mg/L TDS, and these samples are present in all parts of the U.S., with particularly high densities of groundwater samples occurring in Dakotas, Texas, the Central Valley in California, and southeastern Kansas.[10] The vast majority of lower TDS brackish water provides a viable option to meet freshwater demand using low-energy-demand and cost-effective desalination technologies. For instance, it was reported that over 880 trillion gallons (3.33 trillion cubic meters) of brackish water, with TDS ranging from 1,000 to 10,000 mg/L, is available in 26 major and minor aquifers in Texas.[13] Over 75% of the groundwater in New Mexico, which has been increasingly utilized to meet growing freshwater demand,[14] has been found too saline for utilizations in most cases without proper treatment.[15]

According to the USGS national studies on availability of brackish groundwater in the U.S. and estimated water use, the volume of brackish groundwater with TDS concentration of 500 to 10,000 mg/L is over 800 times the amount of saline groundwater used each year for all uses and greater than 35 times the amount of fresh groundwater used.[9,10,16,17] Thus, increased development of brackish water could dramatically improve the water resilience for communities with limited freshwater supplies and affected by climate change.

In the U.S., most brackish water desalination is for municipal uses; smaller water volumes are processed for industrial applications, including cooling, boiler feed, high-purity water for pharmaceutical and semiconductor manufacturing, and food and beverage production (Figure 1).[18] In addition, 86 new municipal desalination facilities were built from 2010 to 2017 with a treatment capacity of greater than 25,000 GPD (gallons per day or 95 m^3/d) per facility (Figure 2).[7,19] Municipal desalination facilities have been identified in 35 states, with the majority of those plants located in California, Texas, and Florida (Figure 1). Because most installed desalination capacity is municipal facilities, this study focuses on brackish water desalination in the municipal sector.

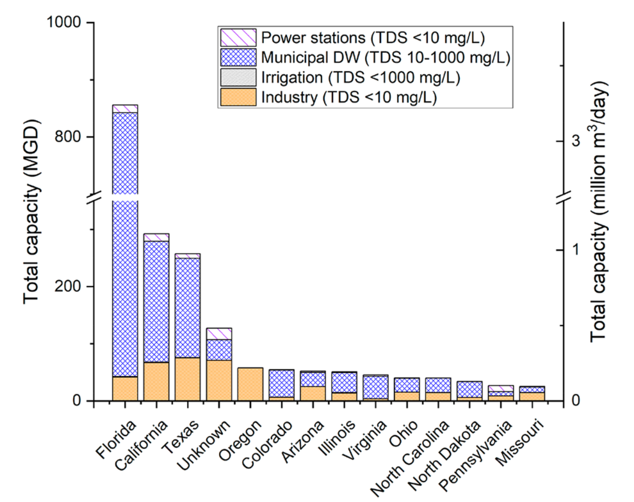


Figure 1. Distribution of brackish/low-salinity desalination capacity by state and end-user types. This chart includes all states up to 85% of the total capacity.[20]

1.3. Current and State-of-the-Art Desalination Technologies. Water quality (both brackish feedwater and product water requirements) affects the selection of desalination

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

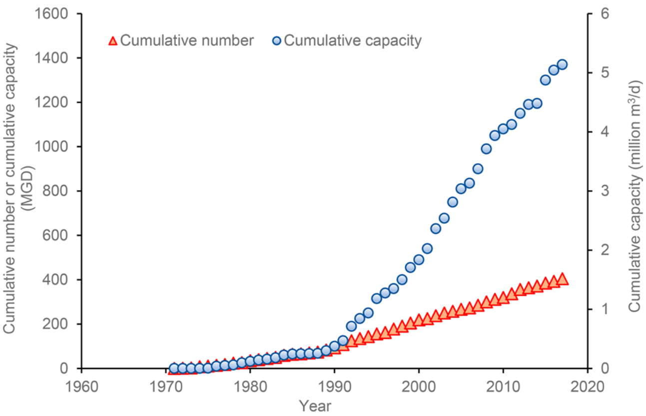


Figure 2. Cumulative numbers and capacity (in MGD and million m^3/d) of municipal desalination facilities from 1971 to 2017 with a capacity of 25,000 GPD (95 m^3/d) and above in the U.S. [7].

processes. The quality of brackish water can vary significantly in different regions and at different depths in the same aquifer, requiring the site-specific choice of desalination technology and brine management.[9] Product water quality differs depending on the end uses of the water. The established water quality goals for potable use are regulated by the USEPA in the Safe Drinking Water Act (SDWA).[21] Individual states and municipalities can set and enforce their drinking water standards if the requirements are at least as stringent as the USEPA's national standards.

For nonpotable uses, a high level of salinity and specific ions, such as high sodium adsorption ratio (SAR) for irrigation, could pose several issues such as increasing soil salinity and sodicity.[22] Contrary to the same high water quality standards in the potable water supply, there is an opportunity in nonpotable uses to supply water with a fit-for-purpose quality either through separate distribution networks or by establishing treatment facilities that yield the fit-for-purpose water close to the point of the desired use.[23]

Desalination systems generally consist of multiple treatment units/steps, including pretreatment, desalting unit (membrane and thermal desalination processes), post-treatment, and brine disposal/reuse. In the U.S., the primary desalination processes are membrane-based, including pressure-driven and electric-driven. Brackish water reverse osmosis (BWRO) dominates municipal desalination applications and makes up more than 85% of the installed systems to date.[7] Nanofiltration (NF) and electrodialysis reversal (EDR) are also implemented for softening and removing salts and specific contaminants (e.g., nitrate) depending on brackish water quality. Because RO (or NF) and EDR have been the most cost-effective desalination methods for the last 30 years, these two technologies are studied as the baseline to investigate the research needs and improvements for brackish water desalination.

RO and NF are pressure-driven processes, utilizing non-porous, semipermeable membranes to remove contaminants via a diffusion-controlled separation process. RO membranes can effectively remove nearly all dissolved organic and inorganic contaminants in water and produce high-quality permeate.[24] NF membranes were developed as a variant of RO membranes with reduced rejection characteristics but required lower operating feed pressure at lower energy costs than RO. NF is well suited for removing hardness, dissolved organic carbon (DOC), and precursors of the disinfection byproduct (DBP).[19]

Electrodialysis (ED) and EDR are electrically driven membrane processes that remove dissolved solids using cation- and anion-selective membranes under the influence of electrical potential.[25−28] Unlike RO and NF, ED or EDR does not provide a barrier to pathogens, suspended solids or noncharged, nonionic constituents, such as silica and organics.[29,23,30]

ED or EDR has been used primarily to desalinate brackish waters and applied in specialty applications, such as removal of nitrate, fluoride, or radionuclides. ED or EDR has a high tolerance of silica, hardness, chlorine residual, and organic matter; therefore, it could achieve a higher water recovery of 85−95% compared to a typical RO recovery of 75−85% during treatment of brackish water.[23,26,31−34]

Pretreatment is crucial to reduce membrane fouling and scaling caused by colloidal particles, organic matter, and sparingly soluble salts such as silica, calcium sulfate, calcium carbonate, barium sulfate, strontium sulfate, iron oxides, calcium phosphate, and calcium fluoride, which are commonly present in brackish water.[35−38] Though fouling and scaling are site-specific, studies showed that the fouling and scaling could reduce the membrane performance and increase 20% to 30% operating and maintenance (O&M) cost.[39,40] Several methods have been developed to control membrane fouling and scaling, such as pretreatment of feedwater, membrane monitoring/cleaning, development of new antifouling membranes, and optimization of operating conditions.[41−44] Common pretreatment for brackish water includes media filtration, addition of acid/antiscalant, softening, and disinfection.[36,38,45,46] Periodic chemical cleaning (e.g., every 3−4 months) is needed to restore membrane performance.

Furthermore, RO permeate exhibits side effects such as lack of essential micronutrient minerals (e.g., magnesium), high corrosivity, and incompatibility during blending with other water sources in the distribution system. Common post-treatment requires one or a combination of recarbonation, remineralization, corrosion control, disinfection, and water quality polishing to remove specific remaining contaminants (e.g., boron).

Due to limited water recovery during brackish water desalination, approximately 5% to 25% of feedwater may be wasted as a concentrate (also called reject or brine). The brine disposal substantially loses valuable water resources and energy and causes environmental implications. This water loss also affects permitting of brackish water desalination facilities because raw water withdrawal volumes and concentrate disposal are the key considerations during permitting.[47] The disposal method of the concentrate is determined by its quantity and quality, permitting requirements, geographical and geological availability (e.g., accessibility to ocean or sewer, appropriate geology for deep-well injection, and availability of land uses), costs, and potential impacts on receiving water body, soil, or beneficial use.

Most desalination concentrate ends in conventional disposal options (>98%), i.e., surface discharge, sewer, subsurface injection, evaporation pond, and land applications.[7] The surface discharge methods are increasingly limited by more stringent regulations, concerns of environmental impacts, and lack of dilution of the receiving water bodies. Deep-well injection (DWI) into a geological formation that isolates the desalination concentrate from drinking water aquifers may be

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

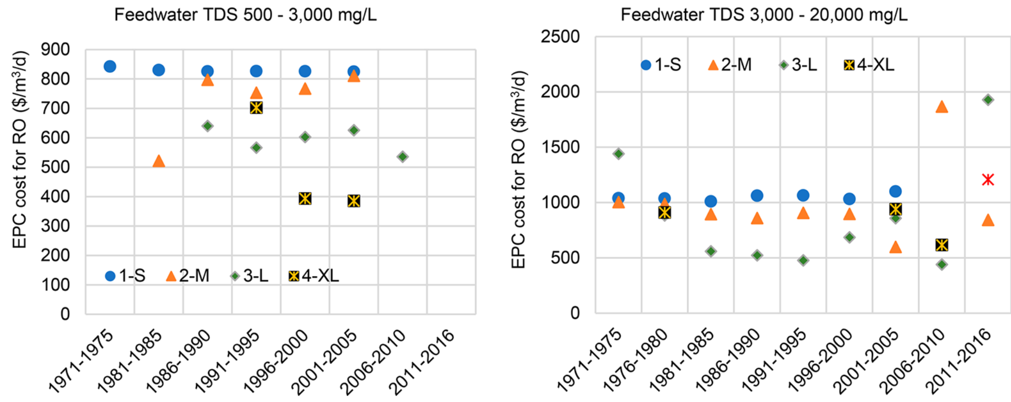


Figure 3. Time series (project award date) of EPC cost per unit of capacity by RO facility size and salinity range.[20] Note: plant sizes: small (S) ≤ 0.22 MGD (1,000 m^3/d), medium (M) 0.22 to 2.2 MGD (1,000−10,000 m^3/d), large (L) 2.2 to 11 MGD (10,000−50,000 m^3/d), and extralarge (XL) ≥ 11 MGD (50,000 m^3/d).

increasingly implemented for inland facilities. However, DWI is typically expensive and often limited to larger facilities (brine volume >1 MGD). It requires appropriate geological formation and confined saline water aquifers (such as in Texas and Florida) and is not feasible for areas of elevated seismic activity or near geologic faults. The permitting of DWI is also becoming more stringent because of the perceived potential for leakage to and contamination of nearby water supply aquifers.

The challenges associated with brine disposal options have limited the implementation of desalination processes to enhance urban water infrastructure portfolios. Innovative technologies to improve water recovery and achieve zero liquid discharge (ZLD) are needed to overcome the barriers of implementing desalination technologies. Higher than 90% water recovery can be achieved using extensive pretreatment, such as softening with lime and ion exchange (IX).[48,49] Concentrate volume can be further minimized using secondary RO or ED and thermal concentrators. For example, the combination of BWRO with ED[50] or a brine evaporator[51] can achieve a water recovery of 90−98%. Using a thermal crystallizer and evaporation ponds can reduce the brine volume to <1%. In addition, various innovative processes have been developed and demonstrated to achieve higher water recovery while reducing scaling and energy intensity, such as vibratory shear-enhanced processing,[52,53] tubular RO membrane and slurry precipitation and recirculation RO,[54] electrodialysis metathesis,[55] closed-circuit desalination technology,[56] and flow reversal RO.[57] For example, semibatch processes such as closed-circuit reverse osmosis can reach a water recovery higher than 90% with lower energy consumption than a standard continuous once-through RO process.[56]

1.4. Costs of Desalination. The desalination costs highly depend on feedwater quality (e.g., TDS), pretreatment, concentrate disposal, and plant size. Figure 3 illustrates the time series of the Engineering, Procurement and Construction (EPC) costs per unit of capacity (m^3/d) by facility size and for water of different salinity.[20] These costs reported in DesalData do not include the costs associated with permitting, site preparation, and financing. The facility data are organized into four size categories: small, medium, large, and extralarge. DesalData defines the TDS range for river/low-saline water as 500 to 3,000 mg/L, while the range is 3,000 to 20,000 mg/L of TDS for brackish/inland. As many municipal desalination facilities in the U.S. are designed to treat water with TDS below 3,000 mg/L,[7] both categories of source water are included in the plots. The data quality is not uniform over the full range of time plotted; for years through 2005, about 95% of facilities in the database include a value for the EPC cost, whereas the percentage drops to fewer than 5% for 2006 and beyond. For the river/low-saline water with TDS less than 3,000 mg/L, the EPC costs retained relatively stable for small- and medium-size desalination facilities (∼\$800/m^3/d), and the costs decrease with increasing facility size to \$600/m^3/d and \$400/m^3/d for large and extralarge facilities, respectively. For the brackish/inland water with TDS of 3,000 to 20,000 mg/L, the EPC costs showed the same trend as the lower TDS water desalination with the economy of scale. The EPC costs of small- and medium-size desalination facilities are in the range of \$900 to \$1150/m^3/d, higher than desalting lower salinity water due to higher energy demand resulting from higher osmotic pressure. The EPC costs varied significantly for the facilities built after 2006, likely due to costs for contraction and concentrate disposal.

2. METHODS

This study initiated a comprehensive literature review to investigate current and emerging technologies for brackish water treatment and uses. Data were collected from peer-reviewed manuscripts, technical reports, engineering contracts, government reports, news releases, databases of national and regional water resources and quality, desalination databases, and surveys. The study was further supported by expert elicitation through meetings, virtual and in-person workshops, and structured interviews engaging experts from industry, national laboratories, government, and academia to gain insights that may not be in the public domain. They helped identify and establish future research priorities for brackish water desalination. They also provided insights into quantitative data to support industry analysis, baseline assessments, and the case studies.

2.1. Case Study Selection. The baseline study aims to characterize the current state-of-the-art technologies of brackish water desalination for municipal uses and identify challenges and opportunities for achieving specific pathways regarding LCOW, electricity intensity, and water recovery. Three facilities were selected for case studies to provide baselines and investigate the current state of brackish water desalination processes. These are the Kay Bailey Hutchison desalination plant (KBHDP) in Texas, the Eastern Municipal

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

Table 1. Summary of Brackish Water Desalination Case Studies (Facility Data, Not Modeled Results)

	Kay Bailey Hutchison Desalination Plant	Eastern Municipal Water District Desalters (3)	Irwin Water Works Desalination Plant
Year of Construction/ Operation	2007	2002, 2006, under construction	2016
Design capacity	27.5 MGD (104,099 m^3/d)	Menifee: 3.1 MGD (11,737 m^3/d) Perris I: 5.6 MGD (21,198 m^3/d) Perris II: 3.5 MGD (13,249 m^3/d)	6.0 MGD (22,712 m^3/d)
Desalination Technology	BWRO	BWRO	EDR
Concentrate Management	22 miles (35.4 km) to 3 injection wells and potential full mineral recovery	70 miles (112.7 km) through a pipeline to the ocean	ZLD (secondary RO, thermal concentrator, evaporation ponds)
Feed TDS (mg/L)	2,500−3,600	2,300	690−890
Water Recovery of Desalination Systems	BWRO 83% (99% potential total recovery by adding a proprietary process)	BWRO 70−75% (95% potential system recovery by adding EDR)	EDR 92% (99% recovery by adding secondary RO, thermal concentrator, and evaporation ponds)
Total Capital Investment	$91 million	$143.4 million	$100.1 million
LCOW (in 2020 $/$m^3$)	0.42−0.56[58]	0.80−1.00[59]	~1.50[60]

Water District (EMWD) desalters in California, and the Irwin Water Works (Irwin) desalination plant in California. These facilities were chosen as case studies because they are representative of different treatment sizes (from small to the largest U.S. inland desalination facility), brackish source water quality (e.g., TDS from 690 to 3,600 mg/L with various sparingly soluble minerals), pretreatments (cartridge filters, addition of antiscalants versus softening and IX), desalination technologies (RO versus EDR), and brine management (surface discharge, DWI, and near ZLD). Table 1 summarizes the characteristics of the selected case studies.

2.2. WaterTAP3 Method. The case studies were simulated using WaterTAP3, an open-source model designed to facilitate consistent technoeconomic analysis of desalination treatment trains. Though engineering firms have been evaluating water supply and treatment options using their private, in-house tools for decades, a publicly available standard tool with similar functionality, more flexibility and customizability, and transparent assumptions and methods is needed for a broader range of users including private sectors, academia, government, and nongovernmental organizations. WaterTAP3 provides an analytically robust platform to evaluate water technology costs, energy, and environmental trade-offs across different water sources, sectors, and scales. A more detailed, in-depth discussion of WaterTAP3 can be found in ref 61.

WaterTAP3 simulates a water treatment plant under steady-state conditions to estimate performance and costs by tracking constituents and water flow through a series of unit process "blocks" subject to system constraints. Costs are first represented at the unit process level (i.e., an individual process within the treatment train) and then aggregated to the system level. Cost metrics cover capital investment and annual O&M, including variable costs (e.g., energy, chemicals) and fixed costs (e.g., labor, maintenance). In the model, costs are estimated by costing functions built into each unit process model that can have certain constraints if applicable or necessary. The technical and cost parameters (e.g., assumptions, methods, and equations) in the model are based upon literature values or case-study specific assumptions.[62−75]

At a high level, WaterTAP3 takes source water conditions, unit process-level models of treatment technologies, and system-level technoeconomic assumptions to solve a mass balance optimized around the LCOW. Performance of a given treatment train is evaluated using the LCOW (cost per unit of treated water), electricity intensity (electricity consumption per unit of treated water), and water recovery (proportion of treated flow relative to influent flow).

3. RESULTS AND DISCUSSION

3.1. Case Study Analysis. *3.1.1. Case Study 1: Kay Bailey Hutchison Desalination Plant, Texas.* The Kay Bailey Hutchison Desalination Plant (KBHDP) is located in El Paso, Texas, where the average annual precipitation is less than 250 mm.[76] The El Paso metropolitan area in the desert has been projected to have a drier climate, imposing stress on the local water resources.[76,77] El Paso Water Utilities (EPWU), the local utility, obtains seasonal fresh surface water from the Rio Grande River, draws fresh groundwater from the Hueco Bolson and Mesilla Bolson aquifers, replenishes its aquifer for future water needs with treated wastewater from the Fred Hervey Water Reclamation Plant (e.g., indirect potable reuse), and is preparing to implement direct potable reuse. Due to continuous water stress (e.g., depletion of fresh aquifers and extended periods of surface water unavailability) and projected population growth, water importation is also considered as a supply option after 2050.[78] The severe water scarcity justifies the deep interest and continuous effort in desalination of local brackish groundwater to maintain self-sufficiency.

The KBHDP, jointly owned by El Paso Water and the Fort Bliss U.S. Army installation, was opened in 2007 to address population growth, chronic droughts, saline water intrusion into freshwater aquifers, and potential water emergencies.[58] The KBHDP is the largest inland brackish groundwater RO desalination plant in the U.S., with a design capacity of 27.5 MGD (104,099 m^3/d),[79,80] providing approximately 5% of the total annual water demand of El Paso.[47] The plant typically processes about 8 MGD (30,283 m^3/d) of potable water, and the peak production was 22 MGD (83,279 m^3/d) during a strong freeze in February 2011.[81]

Water Quality and Treatment. Sixteen production wells and 16 blend water wells feed groundwater from the Hueco Bolson Aquifer to the KBHDP facility. The TDS concentrations of the groundwater wells vary between 2,000 mg/L and 4,000 mg/L, which results in a feedwater TDS of 2,500−3,600 mg/L to the RO system. The groundwater is primarily NaCl type with $CaSO_4$ as the secondary mineral. The dissolved

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

silica concentration is approximately 30 mg/L, limiting the RO water recovery to 82.5%. Table S1 shows the high-level water quality data for the KBHDP before and after treatment.

The KBHDP can produce 27.5 MGD (104,099 m^3/d) of drinking water when operating at full capacity, which consists of 15.5 MGD (58,668 m^3/d) of permeate blended with 12 MGD (45,420 m^3/d) of groundwater to stabilize the water by adding alkalinity and hardness back into the water (Figure 4).

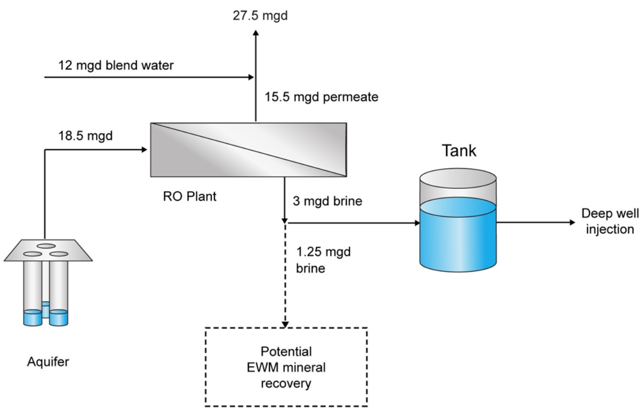


Figure 4. High-level process flows at the Kay Bailey Hutchison Desalination Plant.

Groundwater for blending is supplied from wells with TDS from 800 to 1,600 mg/L, located at Fort Bliss, separate from the wells that provide the RO feedwater.[80] The amount of blending has typically been controlled to limit chloride in the treated water to 270 mg/L.[80]

Process Details. Pretreatment processes include sand strainers (media filtration), 15 μm cartridge filters, and the addition of antiscalant to control silica scaling. The desalination system used 8″ Hydranautics ESPA1 membranes until 2019/2020. There are five RO trains constructed in a two-stage configuration, 48:24 pressure vessel array (Table S2). Each pressure vessel has seven elements. Each train is designed to produce 3 MGD (11,356 m^3/d) at approximately 82.5% recovery. Permeate throttling controls the permeate flow between the first and second stages. The first stage pressure is roughly 170−185 psi; the first stage permeate throttling is 30−40 psi to increase the flux in the second stage and overall product water quality. Post-treatment consists of adding caustic soda for corrosion inhibition and sodium hypochlorite for disinfection.

In 2019, after approximately 13 years of use, the Hydranautics membranes were approaching the end of their service life and were replaced with 8″ Toray TMG20D-440 membranes. The KBHDP is in the process of installing interstage booster pumps (ISBs) between the first and second stages of the RO units to provide the required pressure for optimal membrane performance.[80] The ISBs will make automatic speed adjustments to allow operation in various future water quality conditions.[80,81] The new membranes and interstage boosters are expected to enable a 10% capacity increase in the future.[80] The costs and performance data in this study are based on the Hydranautics membranes used to date.

Brine Management. The KBHDP produces roughly 3 MGD (11,356 m^3/d) of concentrated brine, disposed of through gravity-driven DWI. This brine is currently first stored temporarily in on-site tanks, then pumped approximately 22 miles (35.4 km) from the plant to a surface injection facility located near the Texas−New Mexico border, and finally injected into the Fusselman and Montoya formations. The DWI facility has three disposal wells ranging from roughly 3,700−4,000 feet (1,128 m ∼ 1,219 m) in depth,[58] each with a 300,000 gallon (1,136 m^3) storage tank as a backup in case the brine flow exceeds the design specification. Remote concentrate disposal was chosen because it is less costly and has a lower environmental impact than evaporation ponds. However, there is the possibility of valorizing some of the brine constituents, a concept that is being actively pursued (see Potential for Mineral Recovery).

Cost Data. Table 2 provides a high-level view of the costs to build the plant's infrastructure. The reported water production

Table 2. Total Capital Investment to Build the KBHDP Plant (in 2007 U.S. dollars)[58]

Infrastructure Element	Cost
Production Wells and Collectors	\$32 million
Plant and Near-Plant Pipes	\$40 million
Concentrate Disposal	\$19 million
Total Capital Investment	\$91 million

cost was \$1.50/kgal (\$0.40/m^3) when the plant opened in 2007.[82] With time, the salinity and chloride concentrations of the plant's feedwater increased as the groundwater table decreased and deeper wells had to be redrilled.[80] After eight years of operation, the water cost was roughly 1/3 higher at \$1.99/kgal (\$0.53/m^3) due to deterioration of membrane performance and an observed increase in the TDS in the feedwater from 2,000−2,500 mg/L to 2,500−3,600 mg/L.[83] It is estimated that the feedwater TDS for the plant's source wells may double from 3,000 mg/L to 6,000 mg/L in the next 50 years because of aquifer depletion.[80] The total capital cost of developing the brine management and disposal system was roughly \$19 million. The annual O&M cost of the brine system is approximately \$166,000 (mostly electricity for the pumping station and propane for the operating injection facility).[84]

Potential for Mineral Recovery. The current value of KBHDP's output is for municipal drinking water; however, there is the possibility of economically extracting minerals and chemicals from the brine, which would reduce the overall cost of production if a revenue stream could offset the treatment costs. In addition, a reduction in concentrate volume for disposal can recover additional water from the concentrate and prolong the lifetime of the injection wells. The Enviro Water Minerals Company (EWM) explored the possibility of extracting valuable commodities from the RO concentrate and increasing potable water production (Figure 5). The resource recovery demonstration plant is located near the KBHDP and designed to treat an influent of 1.3 MGD (4,921 m^3/d) of raw brackish water with TDS of 2,500 mg/L and ∼1.3 MGD (4,921 m^3/d) concentrate from the KBHDP plant with TDS of ∼12,000 mg/L (Figure 4). The main process units include an air stripper for alkalinity removal, a softener and NF for hardness separation, RO and EDR for water production and NaCl brine generation, bipolar electrodialysis for acid and base production, and gypsum/magnesium reactors and settlers. The plant aimed to recover potable-quality water (TDS < 800 mg/L) with roughly 99% water recovery, caustic soda (50% concentration), hydrochloric acid (35% concen-

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

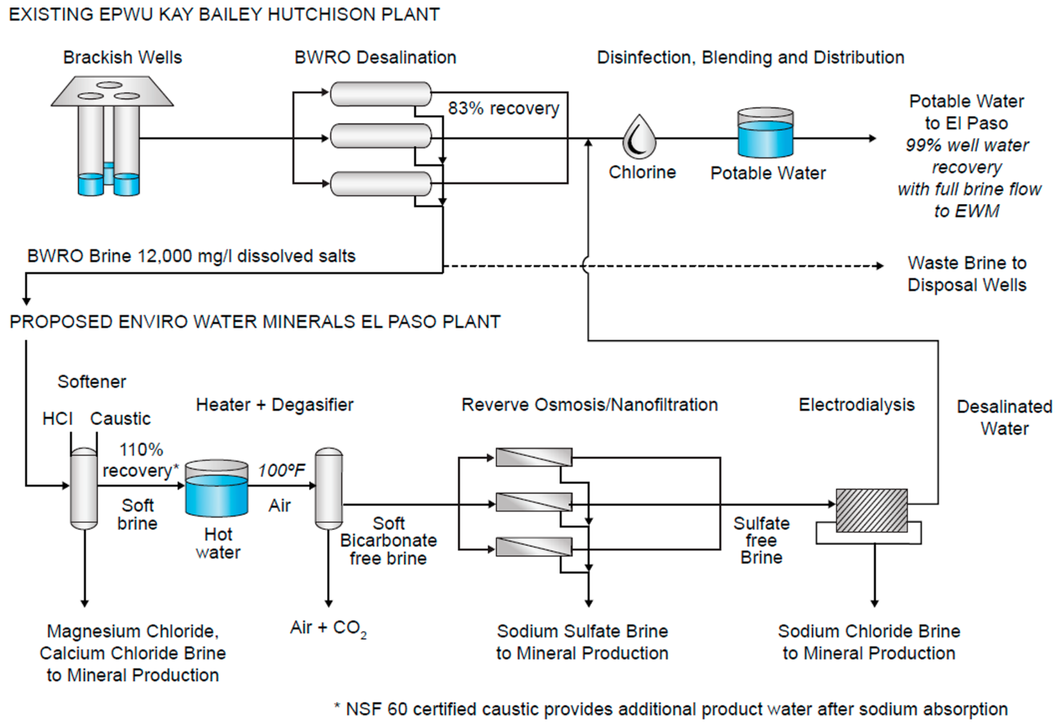


Figure 5. Overview of proposed valorization of the KBHDP RO concentrate.

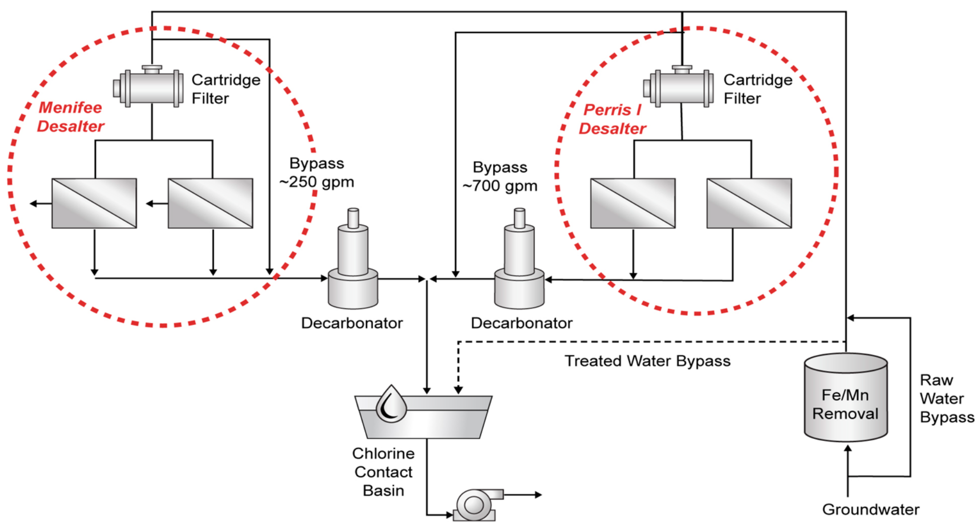


Figure 6. High-level process flows at the EMWD desalters.

tration), gypsum (high purity, 100% soluble), and magnesium hydroxide (98% purity, 56% solid).[85] Due to water treatment equipment problems and operation complexity, the plant did not open after a four-year effort and $65 million in expenses.[86]

Although the EWM's effort for the KBHDP case was not successful, brine transformation and valorization are worth investigating. There are several advantages associated with the beneficial reuse of RO concentrate: (1) It can reduce the operating cost of brine disposal (e.g., annually $166,000 of electricity for the pumping station and propane for operating the DWI facility for the KBHDP). (2) The treated RO concentrate would not be a waste product and can enhance the overall water recovery of the desalination plant, supplementing additional water resources for water-stressed regions. (3) If the desired mineral products can be extracted from the RO concentrate, they have the potential to generate revenues in mineral markets that can offset treatment costs and make the process profitable. For example, two companies reached supply agreements with the EWM as the sole receiver or exclusive distributor of all hydrochloric acid and caustic soda production, respectively, if successfully produced in the EWM facility. It was anticipated that customers exist to purchase products recovered from the brine in the nearby regions. In December 2019, the Critical Materials Corporation (CMC) bought the plant's equipment and is redesigning and rebuilding it.[86]

Future Plans. In April 2020, Texas Governor, Greg Abbot, announced $2.05 million in grant funding to expand the KBHDP to meet the water requirements of the growing number of military installations and the resulting influx of

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

people into the area.[87] Adding \$2.05 million from the Bureau of Reclamation and \$4.1 million from El Paso Water itself, total funding for the project comes to \$8.2 million. The first step in the two-part expansion of KBHDP is the construction of a pipeline, the Blend Well Collector Pipeline, which will carry source water from roughly 7 miles (11.3 km) away to the plant. The second step in the expansion is the addition of another RO skid.[87] When the expansion is complete, the KBHDP will have a production capacity of 33.5 MGD (126,811 m^3/d), up from its current capacity of 27.5 MGD (104,099 m^3/d).

3.1.2. Case Study 2: Eastern Municipal Water District, California. The Eastern Municipal Water District (EMWD) is located in the dry inland region of Southern California with a growing population. The utility currently serves approximately 800,000 people across 555 square miles (1,437 km^2).[88] As of 2018, the EMWD imported roughly half of its water through costly long-distance transport, with the other half coming from various local sources that will be increased to enhance flexibility and reliability of supply and reduce reliance on imported water. Local sources include two collocated brackish water desalination facilities in the city of Menifee,[88] which provide 4% ~ 6% of the total annual water demand.

Water Quality and Treatment. EMWD currently has two desalters—the Menifee and Perris I desalters—located at a single facility served by 12 groundwater wells. The existing desalination plant configuration is shown in Figure 6. EMWD is in the process of adding a third desalter and is also considering alternatives to its current brine disposal method, which sends the brine 70 miles (112.7 km) through a pipeline to the ocean. Table S4 shows the water quality data for the EMWD plant's groundwater before treatment.[89] The TDS concentration of the RO influent is approximately 2,300 mg/L, which results in RO concentrate TDS of 6,000−8,000 mg/L. The groundwater is classified as very hard and has a dissolved silica concentration of 61 mg/L. The presence of iron (~0.4 mg/L) and manganese (~0.12 mg/L) along with other sparingly soluble minerals in the groundwater can cause severe membrane scaling and limit RO water recovery.

Process Details. The Menifee desalter was constructed in 2002 and was designed to process 3.1 MGD (11,735 m^3/d) using 476 RO elements. The Perris I desalter was constructed in 2006 and can process 5.6 MGD (21,198 m^3/d) using 720 RO elements. Water recovery is roughly 70−75% due to a high scaling potential.[59] Both desalters had their RO membranes replaced in October 2017 to address waning production capacity and reduce downtime for cleaning.[90]

High iron and manganese concentrations, which also exacerbate silica precipitation, have damaged some desalter membranes, resulting in several groundwater extraction wells remaining offline.[91] The EMWD was awarded a grant of \$10 million for construction of the iron and manganese removal facility, which began operation in 2014. The facility has allowed EMWD to place four wells back into active service. The system currently removes 25,000 tons of salt from the influent water each year.[92] Post-treatment consists of decarbonation followed by chlorination.

Brine Management. EMWD faces challenging brine management issues for the existing and planned desalination facilities. It currently sends the RO concentrate from the desalination plants 70 miles (112.7 km) through the Inland Empire Brine Line—formerly known as the Santa Ana Regional Interceptor (SARI)—to a treatment facility on the coast in Orange County.[93] The treated concentrate is then disposed of in the ocean, losing a water resource of 815 million gallons per year. The brine line is operated by the Santa Ana Watershed Project Authority, of which EMWD is a member. The Inland Empire brine line has a capacity of 32.6 MGD (123,404 m^3/d) and serves six desalters and industrial dischargers, including the two EMWD desalters.[92]

EMWD has secured rights to 5.9 MGD (22,334 m^3/d) of pipeline capacity and is currently disposing of about 1.7−2.3 MGD (6,355−8,706 m^3/d) of desalter brine into the brine line.[94] EMWD's brine disposal costs are high, including \$8.6 million/year (~\$3.75/gallon) for pipeline use and \$1.05 million/year for fixed O&M costs.[92] EMWD expects to need 4.5 MGD (17,034 m^3/d) at full capacity once the third desalter starts operating.[92] Besides the limited pipeline capacity to meet long-term brine production needs and high cost (expected to be more expensive in the future), there are issues with solids precipitation and internal pipeline scaling,[95,96] caused by the already oversaturated brine in the SARI line. Severe scaling has the risks of hindering sustainable brine management and increasing SARI maintenance cost.

With solids precipitation and pipeline scaling in the SARI, high disposal cost, and growing water demand in EMWD's service area, relying solely on an expensive brine line with limited capacity is not sustainable. Consequently, EMWD has been considering on-site brine recovery as the future alternative and actively testing treatment options for brine handling, focusing on investigating brine volume reduction technologies to enhance overall water recovery of the desalination systems.

During 2005−2007, EMWD evaluated options for a ZLD system.[89] A wide range of existing and emerging water treatment technologies were evaluated, including (1) at pilot-scale: secondary RO and EDR and seeded RO; (2) at bench-scale: forward osmosis and membrane distillation; and (3) by desktop modeling: brine concentrators, crystallizers, evaporation ponds, and SAL-PROC (a residual recovery process). A cost analysis model was developed based on individual treatment modules for each process alternative, with 14 process trains evaluated. Total annual costs ranged from \$5.4 million to \$8.3 million.[89] These figures represent the sum of the amortized capital annual costs over 30 years plus O&M costs and do not consider the revenue generated from recovered water.

Though the previous investigation demonstrated brine volume reduction potential, chemical consumption and waste solids generation brought challenges to operations and maintenance. In 2015, EMWD completed a 9-month pilot-scale demonstration of AquaSel brine concentration technology with significantly reduced chemical usage and solids produced at the Menifee desalter. AquaSel is a proprietary process developed by General Electric (GE) that uses EDR and a precipitator to remove solutes, reducing scaling issues. The test was considered a success, with the system achieving 95% overall recovery of brackish groundwater through improved brine concentration, up from the current water recovery of 75%. Typical membrane fouling and hydraulic issues were mitigated, and the average TDS of the pilot plant's product water was approximately 1,500 mg/L, which is compatible with raw well water for blending.[92,97]

Cost Data. In 2007, the desalters' infrastructure construction costs were as in Table 3. The brackish water supply cost in EMWD is \$3.11 ~ \$3.79/kgal (\$0.82 ~ \$1.00/m^3), and

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

Table 3. EMWD Infrastructure Costs (2007 U.S. dollars)[59]

Infrastructure Element	Cost	Notes
Menifee Desalter	$ 11,200,000	
Perris I Desalter	$ 26,200,000	
Perris II Desalter	$ 29,500,000	After completion
SARI, Treatment & Disposal	$ 28,800,000	Santa Anna Regional Interceptor brine line
Desalter Wells (Shared)	$ 19,200,000	Source wells
Transmission Pipelines (Shared)	$ 18,400,000	Source conveyance lines
Reach 4 Brine Line	$ 7,800,000	Brine line
Moreno Valley Brine Line	$ 2,300,000	Brine line
Total Capital Investment	$143,400,000	

the desalination operating cost is \$1.55/kgal (\$0.41/m^3).[92] The current value of the desalter output is for municipal drinking water; however, economically extracting minerals and chemicals from the RO concentrate may be possible.

Future Plans. Following extended droughts, EMWD decided to add a third desalter in 2015. The Perris II treatment facility will be located adjacent to the existing plant, bringing some synergies and cost savings, including a holding/percolation pond, joint operations building, brine pump station, finished water and brine pipelines, and on-site electricity.[92]

Perris II is currently under construction, and it will initially be connected to the Inland Empire brine line, although the goal is ultimately on-site brine recovery. The new RO plant is designed to process 3.5 MGD (13,249 m^3/d) water from four production wells with a combined capacity of 4.32 MGD (16,353 m^3/d). In 2021, EMWD received a \$25 million Federal Authorization for South Perris Desalination Program.[98] The recent passage of the Water Resources Development Act increases the federal support for EMWD's South Perris Desalination Program from \$25 million to \$50 million. Federal funds will be used for additional water supply wells, pipelines, and a new brine minimization technology that will increase local water supply availability and further reduce EMWD's dependence on imported water supplies. The funding supports new technology to bring that recovery rate from 75% to more than 90%.[98]

3.1.3. Case Study 3: Irwin Water Works Desalination Plant, California. The Irwin Water Works (Irwin) project is located at the U.S. Army's Fort Irwin and National Training Center (NTC), about 130 miles (209 km) northeast of Los Angeles, California. It was developed by the U.S. Army Corps of Engineers and CDM Contractors. Construction started in July 2013, and it was commissioned in 2016. Water demand fluctuates based on troop training rotations and seasonal irrigation. However, the NTC is set to expand as the desert conditions mimic global military arenas for a good training environment, with increased water demand in the future. The plant is designed for a water production capacity of 6 MGD (22,712 m^3/d), though the flow varies with average daily throughput from 2 MGD (7,571 m^3/d) to 2.5 MGD (9,464 m^3/d).

Water Quality and Treatment. Fort Irwin has been obtaining its brackish groundwater via eight wells from three closed basins (Irwin, Bicycle, and Langford) since 1941. Issues related to elevated levels of fluoride (5 mg/L), arsenic (25 μg/L), nitrate (20 mg/L), silica (52 mg/L), and TDS (~690 mg/L), combined with land subsidence, and reduced water levels from withdrawing water at a greater rate than recharge, have led to multiple hydrology and process reviews. Table S6 shows the water quality data for the Irwin plant as influent, effluent, and waste from the EDR process (principal drinking water

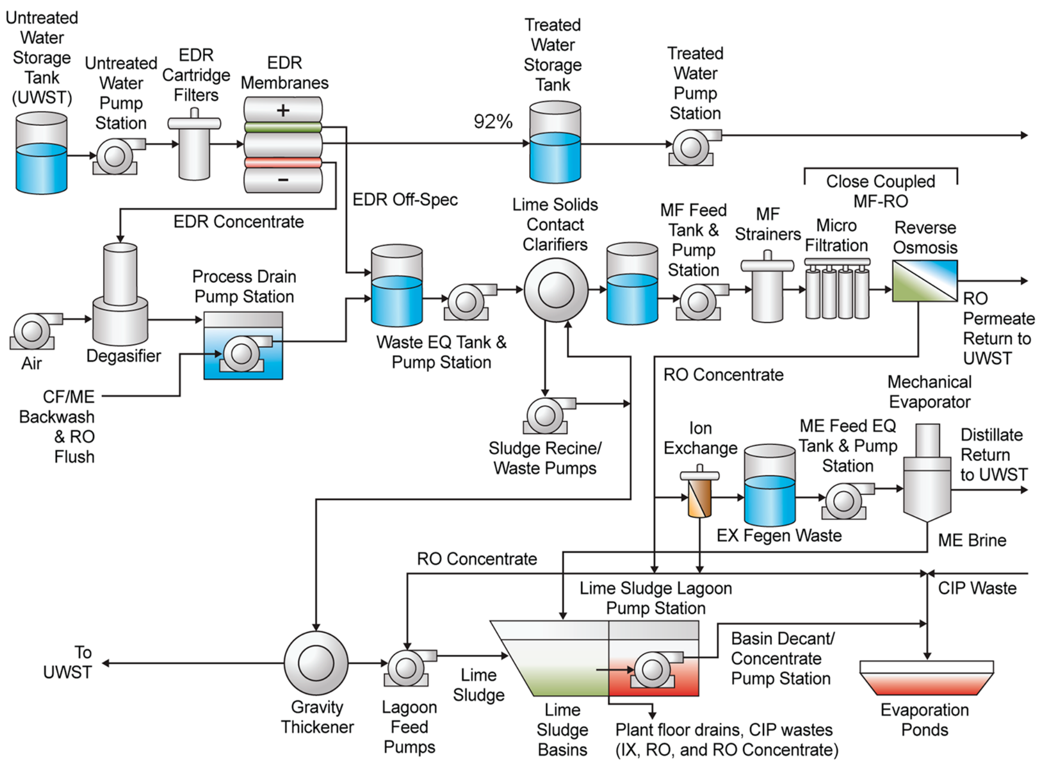


Figure 7. Process flow of the Irwin Water Works desalination plant.

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

Table 4. Overview of Case Study Data and WaterTAP3 (WT3) Results (in 2020 U.S. Dollars)

		KBHDP		EMWD		Irwin	
Analysis Parameter	Units	Facility Data	WT3 Estimate	Facility Data	WT3 Estimate	Facility Data	WT3 Estimate
Total Capital Investment (TCI)[a]	MM$	113.6[a]	123.3	113.9[a,b]	109.7[b]	108[a]	76.3
Operations & Maintenance	MM$/Year	6.6	6.2	3.8	4.0	4.3	5.6
Levelized Cost of Water	$/m^3$	0.42−0.56	0.38	0.8−1.0	1.24	1.5	1.18
Electricity Intensity	kWh/m^3$		0.85		1.50		3.5
Inlet (overall) Water Recovery	%	90	90	70−75	75	99	99

[a]Note: The total capital investment (TCI) was converted to 2020 U.S. Dollars using the CPI Inflation Calculator. [b]Perris II Desalter was not included in this table (facility data and modeling for the EMWD case study).

production process) before subsequent softening and secondary RO treatment.

Fort Irwin previously had potable and domestic water systems. The former was processed through a RO system at 150,000 GPD (568 m^3/d) with 60% water recovery (i.e., 90,000 GPD or 341 m^3/d) drinking water and 60,000 GPD (227 m^3/d) waste.[99] The RO system was designed to remove the naturally occurring fluoride found in many Fort Irwin wells to below 2.0 mg/L, the State of California MCL. In 1996, the USEPA broadened the definition of "consumptive use" to include bathing, cooking, and dishwashing. This regulatory change at the federal level was followed by permit action by the State of California (agency of primacy) in January 2004. The 2004 water system permit detailed that the two-water system approach was no longer in compliance with regulatory requirements; a single water system was now required. In early 2006, the USEPA promulgated new standards for arsenic in drinking water, lowering the MCL from 50 μg/L to a new limit of 10 μg/L, rendering the Fort Irwin water system out of compliance for arsenic in addition to fluoride. The existing RO plant would now fall well short of the capacity to meet the entirety of Fort Irwin water needs, which led to the U.S. Army requiring a new drinking water plant.[100]

Passive, low-energy technologies were among the first reviewed as a solution to Fort Irwin's water needs, chief of which was an IX process using activated alumina. This medium has a high affinity for both arsenic and fluoride. Potential issues with this technology were identified due to elevated levels of dissolved "reactive" silica.[60] Activated alumina has a higher affinity for silica than both arsenic and fluoride, indicating the media might be filled with silica before fluoride or arsenic. An elevated silica concentration would also diminish RO water recovery. As Fort Irwin lies in an arid region of the Mojave Desert, receiving approximately 4−5 in. (102−127 mm) of rainfall annually, a treatment process achieving high water recovery (i.e., 99.6%) is critical to conserve the area's limited water resource and ensure a long-term sustainable water supply. After bench-scale studies, in 2006, a full-scale pilot trial was completed using an activated alumina and EDR process (no concerns with silica fouling). The results indicated the EDR process provided a robust process for treating groundwater from each basin, either individually or as blends, and was well-suited for producing high-quality water even if raw water quality deteriorates in the future.[101] EDR is reliable and easy to operate with minimal maintenance requirements once the general operating parameters are established. The inherent flexibility of the process allows adjustment of power use (voltage settings) to easily match contaminant removal to meet the water quality goals and optimize power consumption.[102]

The water recovery of the EDR process is 92%.[83] The EDR reject water (brine waste stream) is treated through several downstream processes: air stripping, lime softening, microfiltration (MF), RO, IX, and a mechanical evaporator (ME) as shown in Figure 7. In the RO unit and mechanical evaporator, product waters (RO permeate and distillate) are returned to the raw water storage tank and are blended with the well water. The overall reject from the waste stream process ranges from 0.1%~2%. This waste is sent to evaporation ponds, where the residuals are removed to a permitted landfill. The final product water is disinfected with sodium hypochlorite before delivery to the water distribution system.

Process Details. The system contains four cartridge filters and five EDR trains, achieving a recovery of 92%, with each train having eight lines of EDR stacks (three stacks per line, 600 membrane pairs per stack). Off-spec water (product water that does not meet the quality standard due to reversing the EDR electrode polarity) and EDR concentrate after degassing treatment (removal of alkalinity) go through a lime softening process and then membrane filtrations (strainer + MF) before a secondary RO treatment. RO permeate returns to the untreated water storage tank before the EDR.[83] Despite the multiple pretreatments prior to the secondary RO treatment (75% recovery), the RO elements in the third stage had been replaced after 18 months of operation,[103] signifying operating challenges in reclaiming water from brine using a membrane-based process. The RO concentrate goes to an IX and mechanical evaporator (80% recovery) with distillate returned to the untreated water tank and the brine joining waste from the IX and RO for decanting and ending in the evaporation ponds.

Brine Management. Brine reduction and management was designed to yield an overall 99.6% water recovery. Thus, the final waste has 144 g/L of TDS (see Table S8 for waste constituents). The waste is pumped to nine on-site Class II evaporation ponds, a cost-competitive option for small brine volume, with a double-lined system to prevent percolation from the concentrated brine into the ground. The top liner is a roller-compacted soil cement liner to prevent puncture from equipment during solids removal, followed by a nonwoven geotextile fabric. Next comes two 60-mil high-density polyethylene (HDPE) liners.[104] Finally, a geosynthetic clay liner protects the HDPE liner from compacted native soil. The free-draining vadose zone lies below this system and is monitored for compliance and contaminants.

Cost Data. The total cost to build Irwin in 2016 was $100.1 million − $51 million for the water treatment and $49.1 million for the brine management.[60] The high recovery processes in brine treatment, not common in municipal applications, had almost doubled the capital cost, with increased operating costs.

3.2. WaterTAP3 Modeling Results. As mentioned earlier, the WaterTAP3 assessment tool was used to simulate the

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

technological and economic aspects of the three case studies. This section provides an overview of the model inputs and results. See the Supporting Information (SI) and the online versions of the case studies for more details.

3.2.1. Summary of Modeling Results. As seen in Table 4, the WaterTAP3 model results are close to the actual facility data in those cases where facility data is available. For example, the WaterTAP3 estimate for KBHDP's LCOW in 2020 dollars is $0.38/m^3, whereas the facility's actual cost range was $0.42−0.56/m^3. The other WaterTAP3 parameters in the table are also roughly comparable to facility data, which provides confidence for results obtained from WaterTAP3. The WaterTAP3 financial and operational inputs for the three case studies are summarized in Tables S3, S5, and S7. Table S9 summarizes the important operating parameter inputs from facility data and constraints for the WaterTAP3 analysis.

It should be noted that some cost elements were not included in WaterTAP3 (see the Supporting Information) but likely were included in the capital costs of the facility data. For instance, the Perris II Desalter was not included in the WaterTAP3 simulation for the EMWD case study. The permitting costs were not considered in the model because they are case-specific. The level of uncertainty of the WaterTAP3 model is typically −30% to +50%.

Figure 8 shows that total capital investment (TCI) is by far the single largest component of the LCOW for all three

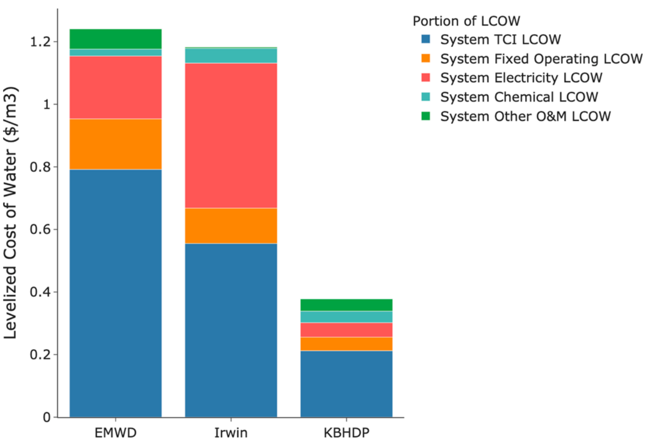


Figure 8. WaterTAP3 estimated LCOW by major cost category.

facilities, constituting 64%, 56%, and 47% of the LCOW for the EMWD, KBHDP, and Irwin, respectively. Among the three desalination plants, the KBHDP has the lowest LCOW, approximately $0.38/m^3, which is 3.3 and 3.1 times lower than the costs of the EMWD and Irwin, respectively, due to the simple pretreatment (sand strainers, cartridge filters, and addition of antiscalant) and post-treatment (blending). The higher LCOW of the EMWD is attributed to expensive brine disposal, pretreatment of oxidative metals (i.e., Fe and Mn removal), and low water recovery, compared to the KBHDP with a similar TDS level in raw water. The high LCOW of Irwin (the lowest TDS in raw water) is due to the capital investment and electricity costs to achieve ZLD of the EDR concentrate. The analysis reveals that the cost of desalination has no set costs and is highly dependent on site-specific conditions (e.g., different pretreatment and brine management options as represented in this study).

In Figure 9, the total LCOW is broken down by the treatment processes used. The principal RO treatment is the

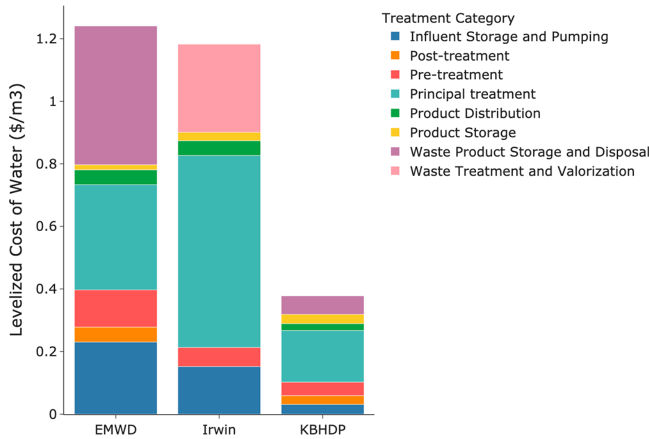


Figure 9. WaterTAP3 estimated LCOW by process area.

largest cost element for the KBHDP, constituting 44% of the total LCOW, followed by brine storage and disposal. For Irwin, the principal desalination and brine treatment constitute the largest cost elements of 52% and 24%, followed by 13% for the influent storage and pumping. The brine management and disposal accounts for the most prominent costs element of 36% for the EMWD; the RO desalination process and pretreatment constitute 27% and 10% of the total LCOW.

Figure 10 shows the energy intensity of the various treatment processes. The principal desalination is a significant

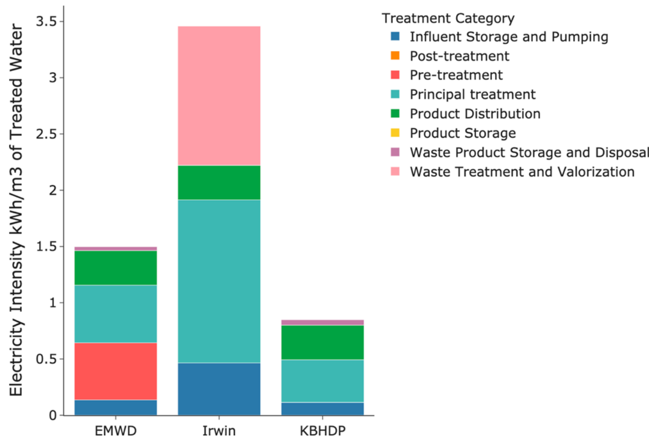


Figure 10. WaterTAP3 estimated electricity consumption by process area.

energy consumer for all three facilities. Energy recovery systems, which are not implemented in these treatment trains, can recover the hydraulic energy in desalination brine to reduce the overall energy intensity in pressure-driven systems. However, unlike seawater desalination commonly equipped with energy recovery systems, regaining the relatively small residual energy from brackish water desalination brine should be scrutinized,[105] considering the initial capital expenditure associated with installing additional equipment and O&M costs. The KBHDP has the lowest energy intensity of 0.85 kWh/m^3. The system electricity intensity of EMWD is 1.5 kWh/m^3, consumed primarily by RO and pretreatment processes. Fort Irwin has the highest electricity intensity of

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

3.5 kWh/m^3, due to the higher energy demand of EDR in the principal treatment to avoid silica scaling, as EDR has a lower cost-competitive advantage than RO in treating low-TDS water (690 mg/L in this case)[106] and additional energy needs for secondary RO, and the thermal evaporator in waste stream processes. The product distribution also constitutes a significant energy consumer for the desalination facilities.

3.2.2. Alternative Brine-Handling Scenarios. Brine management is a key challenge for brackish water desalination, especially as more stringent regulations governing brine disposal are anticipated. In order to better understand the impact of various disposal options on the cost of water and energy use, WaterTAP3 was used to estimate alternative brine-handling scenarios for the EMWD facility, including one option that explores the cost and energy implications of using DWI and three options for achieving ZLD (Figure 11). All four

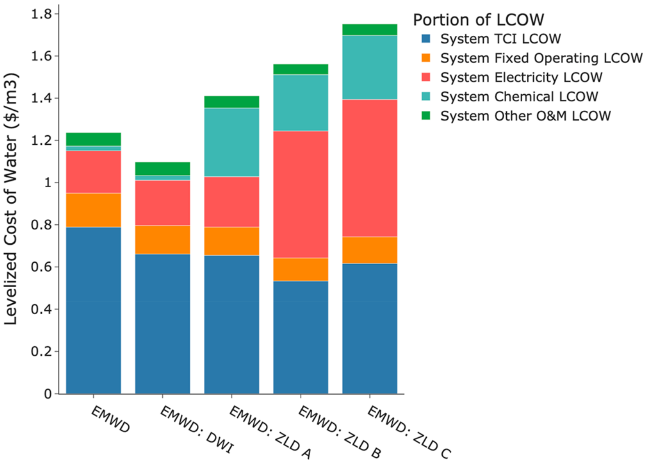


Figure 11. LCOW impacts from various brine-handling options at the EMWD facility, by major cost category: EMWD, base case of existing desalters; DWI, RO1 → Lime Softening → RO2 → Deep-Well Injection (fixed pressure); ZLD-A, RO1 → Lime Softening → RO2 → Evaporation Pond + Landfill; ZLD-B, RO1 → Lime Softening → RO2 → Brine Concentrator → Evaporation Pond + Landfill; ZLD-C, RO1 → Lime Softening → RO2 → Brine Concentrator → Crystallizer → Landfill. Note that the WaterTAP3 model for the EMWD fixed-pressure DWI case used the brine piping costs from the KBHDP plant's existing DWI system to simulate real-world costs for comparison purposes.

of the alternative brine-handling scenarios include lime softening to remove hardness and other scale-forming minerals in the RO concentrate followed by a secondary RO process to improve water recovery of the Menifee desalter to 80.9% and the Perris I desalter to 90.3%. As compared to the base case LCOW ($1.24/$m^3$) for the existing treatment processes and brine disposal via the Inland Empire Brine Line to the ocean, the LCOW would decrease to $1.10/$m^3$ for the scenario of brine disposal through DWI and using lime softening and secondary RO to improve water recovery and reduce the concentrate volume for DWI. The costs would increase to $1.42/$m^3$ for scenario ZLD A (Figure S1) if an evaporation pond and landfill for solids disposal would be used for ZLD instead of DWI. The LCOW would increase to $1.57/$m^3$ for the ZLD-B scenario of using a brine concentrator + evaporation pond + landfill (Figure S2) and $1.76/$m^3$ for the ZLD-C scenario of brine concentrator + crystallizer + landfill for solids disposal (Figure S3). The cost estimates indicate that ZLD is achievable for EMWD but is substantially more expensive than other brine-handling solutions for that facility, such as DWI. The higher costs for the ZLD scenarios B and C are associated with the high energy intensity of the brine concentrator and crystallizer, reflecting cost-intensive approaches to achieve ZLD using thermal technologies in municipal applications (Figures 11 and 12). Compared to

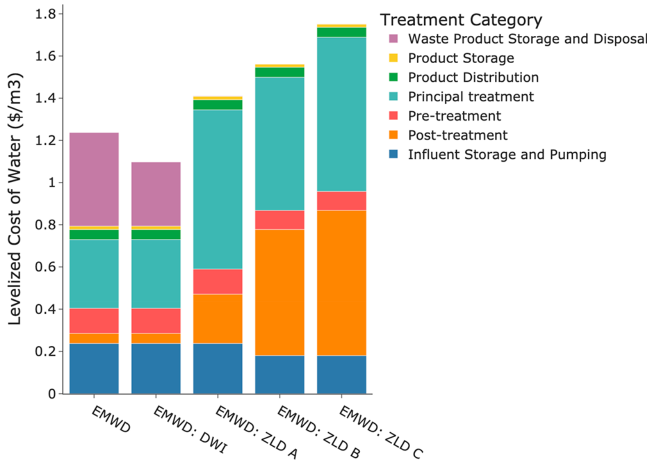


Figure 12. LCOW impacts from various brine-handling options at the EMWD facility, by treatment category.

the LCOW of Irwin, the costs of achieving ZLD for the EMWD facilities are higher due to the high TDS and scaling potential of the EMWD groundwater, thus resulting in high energy demand and extensive intermediate treatment to remove scale-forming minerals in groundwater and brine. Figure 12 illustrates the total LCOW according to the treatment processes used, and Figure S4 displays their energy intensities. Post-treatment adds substantially to the cost of ZLD options for EMWD and has a dramatically higher energy intensity than the two ZLD systems that use brine concentrators.

4. CONCLUSIONS AND RESEARCH PERSPECTIVES

This study evaluates the technical and economic aspects of desalination technologies using the KBHDP, EMWD desalters, and Irwin as case studies to enhance the sustainability of brackish water desalination. The future expansion plans in all of the case studies showed the strong governmental support (federal and state levels) and local impetus (i.e., utilities) for promoting the fast development of desalination.[107] Based on the literature review, case studies, and technoeconomic analysis, brine management is confirmed as a significant challenge that limits the sustainability of desalination processes.

The case studies have three unique brine approaches, DWI for the KBHDP, surface discharge through the SARI pipeline to the ocean for the EMWD, and onsite ZLD in Irwin. Brine discharge through DWI is a viable option for sizable inland desalination plants with large volumes for disposal and appropriate geological formation. However, DWI permitting is challenging for municipal utilities. The USEPA designates Class I wells (the most pertinent) and Class V wells (not common) for subsurface injection of desalination brine, requiring more efforts and resources for permit approval.[108] For instance, the KBHDP had to request an aquifer exempt

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

(AE) permit from both the federal (USEPA) and state agencies (e.g., Texas Commission on Environmental Quality) to discharge brine without meeting the primary drinking water standards under Class V wells regulations. Without the approval of such a water quality exemption, DWI would be more costly with the addition of brine dilution in KBHDP. DWI is also expected to face more stringent regulations in the future, considering the potential safety risk and growing environmental sensitivity. Surface discharge through the pipeline is expensive and has other operation issues in the EMWD case. The scaling and fouling in the internal pipeline impede long-distance conveyance and induce environmental impacts from the antiscalant (primary antiscalant and additional added prior to pipeline transport). Onsite treatment to remove hardness and antiscalant before transport has been proposed to reduce pipeline scaling and fouling and mitigate the risk of eutrophication caused by antiscalants.[96,109] The Irwin case indicated a significant increase in capital and operating costs when a progressive ZLD treatment train was adopted for brine treatment in arid areas. The challenges posed by scaling and fouling issues (especially the silica-induced scaling) in the brine treatment train cannot be reiterated enough, particularly in the second and third RO stages. Mitigation of calcium carbonate scaling requires low pH, while high pH maintains elevated silica in solution. Irwin adopted a high pH control for the RO unit as membrane performance recovery from CIP demonstrated higher effectiveness with calcium carbonate scaling than silica scaling. Considering the highly variable water demand in Irwin and the continuously decreased cost of a small-scale modular desalination skid, it is worth noting that deployment of mobile desalination units plus stationary capacity would be advantageous for less predictable demand scenarios.[110]

The KBHDP and EMWD are actively seeking alternative brine disposal options for brine volume reduction, water reclamation, and mineral recovery. Reducing brine volume for disposal or crystallization to achieve ZLD would eliminate the need for brine conveyance, lower energy intensity, reduce dependence on finite injection well capacity, and enhance resource recovery.

Innovative technologies to improve water recovery, control scaling, and reduce the costs for achieving ZLD are needed to overcome the barriers of implementing desalination technologies. However, the costs to achieve ZLD using thermal technologies can be prohibitive for municipal applications, as shown in the alternative brine-handling scenarios for the EMWD facility. Brine minimization using high-recovery desalination processes can reduce the costs for thermal crystallization and other ZLD processes. Separating and extracting valuable minerals and producing chemicals from concentrate streams can further increase product water yields, reduce disposal costs, and create revenue streams from commercial product sales. Depending on the source water quality and location, brine may contain a wide variety of constituents for potential recovery and valorization. Recovering high-concentration elements to produce chemical products such as NaCl, $CaCl_2$, $CaSO_4$, KOH, $Mg(OH)_2$, SiO_2, and NH_4MgPO_3 is technically feasible and could offset treatment costs.

In addition, generating process chemicals on-site from brine (e.g., Cl_2, H_2O_2, acids, and bases) can reduce transportation and storage costs and mitigate risks related to handling and managing hazardous chemicals. For example, El Paso Water has partnered with private entities to recover minerals from the concentrate of the KBHDP, which will be chemically separated into high-purity, industrial-grade mineral products, including gypsum, HCl, and NaOH solutions.

The economic feasibility of minerals recovery from brine depends on the resource recovered and the processes used. To achieve high purity of the mineral products, the treatment processes can be complex and demand system integration, optimization, operation and maintenance, and compatibility of multi-stage processes. Hence, sustainable brine treatment has low maintenance needs, low energy intensity, and the capability to extract high-market-value products with a certain purity. Substantial fundamental and applied research is needed to enhance the cost-effectiveness, resiliency, and robustness of the mineral recovery technologies.

All three case studies indicate scaling and fouling is another major challenge for brackish water desalination. There is a pressing need for effective technologies to control membrane fouling and scaling. An appropriate pretreatment combination is the key to preventing subsequent fouling and inorganic scaling, and the cost competitiveness of the selected combination should be well assessed. This may include precision separation technologies to selectively remove the scaling and fouling constituents, such as innovative adsorbents for hardness and silica removal. Scaling and fouling can also have a severe consequence in brine management, e.g., surface discharge through a pipeline and mineral recovery from brine. Removal of antiscalant in brine is sometimes required to accelerate the precipitation prior to discharge (as in the EMWD case) or go to the subsequent treatment process for mineral recovery. The presence of antiscalant was found to reduce calcium precipitation and incorporation of magnesium into the calcium precipitate.[111,112] It may cause a deleterious impact on the separation of calcium and magnesium in the EWM project treating the KBHDP concentrate. Antiscalant residual may affect the production of high-purity gypsum and magnesium hydroxide from RO concentrate. The antiscalant can be removed through coagulation[113,114] and an advanced oxidation process (AOP),[109,115] e.g., ozonation, hydrogen peroxide, and photolysis.

Scale formation comprises complex phenomena involving supersaturation, nucleation, crystallization, and precipitation.[116−118] The development of real-time, in operando methods to monitor the precipitation and growth of a scale layer is of great importance to control the fouling and scaling. It requires accurate and real-time monitoring of representative/surrogate parameters to indicate the fouling and scaling potential. There is also a need for digital twins and artificial intelligence to analyze the relative parameters and convert monitoring data into system control and operation optimization.

Though site-specific permitting costs were not considered in the WaterTAP3 model, the regulatory process and permitting of brackish water desalination can be lengthy through federal, state, and local agencies. For example, the KBHDP facility took six years to complete the regulatory process on a case-by-case basis in the state of Texas,[47] while faster permitting would accelerate the deployment of desalination when needed in the future. Changing regulations also affect the development of desalination treatment processes and facilities, as shown in the Irwin case. A comprehensive permitting framework/procedure is needed for inland brackish water desalination in the municipal sector.[47] Proactive planning and modular treatment

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

systems would be preferred to adapt the future desalination modification to evolving legal and regulatory changes.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.1c00326.

Additional information on the three case studies (e.g., water quality data, process parameters, and financial and operational inputs for WaterTAP3) and alternative brine-handling scenarios for the Eastern Municipal Water District case study (PDF)

AUTHOR INFORMATION

Corresponding Author

Pei Xu − *Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico 88003, United States;* orcid.org/0000-0002-4053-9495; Email: pxu@nmsu.edu

Authors

Xuesong Xu − *Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico 88003, United States;* orcid.org/0000-0003-2048-2433

J. Erik Ness − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Ariel Miara − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States;* orcid.org/0000-0001-7089-4765

Kurban A. Sitterley − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Michael Talmadge − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Barbara O'Neill − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Katie Coughlin − *Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States*

Sertac Akar − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

E. M. N. Thiloka Edirisooriya − *Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico 88003, United States*

Parthiv Kurup − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Nalini Rao − *Electric Power Research Institute, Palo Alto, California 94304, United States*

Jordan Macknick − *National Renewable Energy Laboratory, Golden, Colorado 80401, United States*

Jennifer R. Stokes-Draut − *Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsestengg.1c00326

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Alliance for Water Innovation (NAWI), funded by the U.S. Department of Energy, Energy Efficiency and Renewable Energy Office, Advanced Manufacturing Office under Funding Opportunity Announcement DE-FOA-0001905. This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The study was also based on previous research supported by the National Science Foundation Engineering Research Center ReNUWIt (EEC-1028968). The authors are very grateful for the technical support and discussions with the experts and operators in the field. P.X. also acknowledges support from the New Mexico State University through the PESCO Endowed Professorship in the College of Engineering and C. Herb Ward Family Endowed Interdisciplinary Chair Professorship in the College of Agricultural, Consumer, and Environmental Sciences.

REFERENCES

(1) Reilly, T. E.; Dennehy, K. F.; Alley, W. M.; Cunningham, W. L. *Ground-water availability in the United States*; Geological Survey (US), 2008.

(2) Abd-Elhamid, H.; Javadi, A. Impact of sea level rise and over-pumping on seawater intrusion in coastal aquifers. *Journal of Water and Climate Change* **2011**, *2* (1), 19−28.

(3) Alam, S.; Gebremichael, M.; Li, R.; Dozier, J.; Lettenmaier, D. P. Can Managed Aquifer Recharge Mitigate the Groundwater Overdraft in California's Central Valley? *Water Resour. Res.* **2020**, *56* (8), No. e2020WR027244.

(4) Chaudhuri, S.; Ale, S. Long term (1960−2010) trends in groundwater contamination and salinization in the Ogallala aquifer in Texas. *Journal of Hydrology* **2014**, *513*, 376−390.

(5) Inyinbor Adejumoke, A.; Adebesin Babatunde, O.; Oluyori Abimbola, P.; Adelani Akande Tabitha, A.; Dada Adewumi, O.; Oreofe Toyin, A. Water pollution: effects, prevention, and climatic impact. *Water Challenges of an Urbanizing World* **2018**, *33*, 33−47.

(6) AMTA, Future of Desalination in the United States. American Membrane Technology Association (AMTA). Available at: https://www.amtaorg.com/wp-content/uploads/11_Future_of_Desal.pdf. 2018. (accessed 2021-09-08).

(7) Mickley, M. Updated and Extended Survey of U.S. Municipal Desalination Plants. *Desalination and Water Purification Research and Development Program Report No. 207*; U.S. Department of Interior, Bureau of Reclamation, Technical Service Center: Denver, CO, USA, 2018.

(8) Mauter, M. S.; Fiske, P. S. Desalination for a circular water economy. *Energy Environ. Sci.* **2020**, *13* (10), 3180−3184.

(9) Stanton, J. S.; Anning, D. W.; Brown, C. J.; Moore, R. B.; McGuire, V. L.; Qi, S. L.; Harris, A. C.; Dennehy, K. F.; McMahon, P. B.; Degnan, J. R. *Brackish groundwater in the United States*; US Geological Survey, 2017; DOI: 10.3133/pp1833.

(10) Ahdab, Y. D.; Thiel, G. P.; Böhlke, J. K.; Stanton, J.; Lienhard, J. H. Minimum energy requirements for desalination of brackish groundwater in the United States with comparison to international datasets. *Water research (Oxford)* **2018**, *141*, 387−404.

(11) Lapworth, D.; Baran, N.; Stuart, M.; Ward, R. Emerging organic contaminants in groundwater: a review of sources, fate and occurrence. *Environmental pollution* **2012**, *163*, 287−303.

(12) Bexfield, L. M.; Toccalino, P. L.; Belitz, K.; Foreman, W. T.; Furlong, E. T. Hormones and pharmaceuticals in groundwater used as a source of drinking water across the United States. *Environ. Sci. Technol.* **2019**, *53* (6), 2950−2960.

(13) Boettcher, S. J.; Gately, C.; Lizano, A. L.; Long, A.; Yelvington, A. Part 1: Brackish Groundwater Desalination Technical Report. *EENRS Program Reports & Publications. 10*; 2020; DOI: 10.37419/EENRS.BrackishGroundwater.P1.

(14) Kang, M.; Ayars, J. E.; Jackson, R. B. Deep groundwater quality in the southwestern United States. *Environmental Research Letters* **2019**, *14* (3), 034004.

(15) Ali, A. R. B.; Shukla, M. K.; Schutte, B. J.; Gard, C. C. Irrigation with RO concentrate and brackish groundwater impacts pecan tree growth and physiology. *Agric. Water Manage.* **2020**, *240*, 106328.

(16) Maupin, M. A.; Kenny, J. F.; Hutson, S. S.; Lovelace, J. K.; Barber, N. L.; Linsey, K. S. Estimated use of water in the United States in 2010. *U.S. Geological Survey Circular 1405*; 2014; p 56. .

(17) Dieter, C. A.; Maupin, M. A.; Caldwell, R. R.; Harris, M. A.; Vahnenko, T. I.; Lovelace, J. K.; Barber, N. L.; Linsey, K. S. Estimated use of water in the United States in 2015. *U.S. Geological Survey Circular 1441*; 2018; p 65. .

(18) He, Q. C.; Bond, R. G. *Inland desalination & concentrate management*; American Water Works Association, 2019.

(19) Mickley, M. US municipal desalination plants: number, types, locations, sizes, and concentrate management practices. *IDA Journal of Desalination and Water Reuse 2012* **2012**, *4* (1), 44−51.

(20) GWI, Global Water Intelligence (GWI) 2020 DESALDATA. Available at www.desaldata.com. 2020. (accessed 2021-09-08).

(21) USEPA, United States Environmental Protection Agency. Drinking Water Requirements for States and Public Water Systems. Available at: https://www.epa.gov/dwreginfo/drinking-water-regulations. 2021. (accessed 2021-09-08).

(22) Mavi, M. S.; Marschner, P.; Chittleborough, D. J.; Cox, J. W.; Sanderman, J. Salinity and sodicity affect soil respiration and dissolved organic matter dynamics differentially in soils varying in texture. *Soil Biology and Biochemistry* **2012**, *45*, 8−13.

(23) Xu, X.; He, Q.; Ma, G.; Wang, H.; Nirmalakhandan, N.; Xu, P. Pilot Demonstration of Reclaiming Municipal Wastewater for Irrigation Using Electrodialysis Reversal: Effect of Operational Parameters on Water Quality. *Membranes* **2021**, *11* (5), 333.

(24) National Research Council. *Desalination: A National Perspective*; National Academy Press: Washington, D.C., 2008.

(25) Reahl, E. R. Half a century of desalination with electrodialysis. *Ionics Technical Report*; Available at: General Electric Company (GE). http://www.gewater.com/pdf/Technical%20Papers_Cust/Americas/English/TP1038EN.pdf. (Retrieved 2007-10-02). 2006.

(26) Strathmann, H. Electrodialysis, a mature technology with a multitude of new applications. *Desalination* **2010**, *264* (3), 268−288.

(27) Tanaka, Y.; Ehara, R.; Itoi, S.; Goto, T. Ion-exchange membrane electrodialytic salt production using brine discharged from a reverse osmosis seawater desalination plant. *J. Membr. Sci.* **2003**, *222* (1−2), 71−86.

(28) Sata, T.; Sata, T.; Yang, W. Studies on cation-exchange membranes having permselectivity between cations in electrodialysis. *J. Membr. Sci.* **2002**, *206* (1−2), 31−60.

(29) Xu, P.; Capito, M.; Cath, T. Y. Selective removal of arsenic and monovalent ions from brackish water reverse osmosis concentrate. *Journal of hazardous materials* **2013**, *260*, 885−891.

(30) Xu, X.; He, Q.; Ma, G.; Wang, H.; Nirmalakhandan, N.; Xu, P. Selective separation of mono- and di-valent cations in electrodialysis during brackish water desalination: Bench and pilot-scale studies. *Desalination* **2018**, *428*, 146−160.

(31) Xu, P.; Cath, T.; Robertson, A. P.; Reinhard, M.; Leckie, J. O.; Drewes, J. E. Critical Review of Desalination Concentrate Management, Treatment and Beneficial Use. *Environmental Engineering Science* **2013**, *30* (8), 502−514.

(32) Van der Bruggen, B.; Lejon, L.; Vandecasteele, C. Reuse, Treatment, and Discharge of the Concentrate of Pressure-Driven Membrane Processes. *Environ. Sci. Technol.* **2003**, *37* (17), 3733−3738.

(33) Turek, M.; Was, J.; Dydo, P. Brackish water desalination in RO-single pass EDR system. *Desalination and Water Treatment* **2009**, *7*, 263.

(34) Trussell, R. S.; Williams, G. J. Reclaimed Water Desalination Technologies: A Full-Scale Performance and Cost Comparison Between Electrodialysis Reversal and Microfiltration/Reverse Osmosis. *Report of WateReuse Research Foundation Project Number: WRF-08-17*; 2012.

(35) Wenten, I. Reverse osmosis applications: prospect and challenges. *Desalination* **2016**, *391*, 112−125.

(36) Xu, P.; Bellona, C.; Drewes, J. E. Fouling of nanofiltration and reverse osmosis membranes during municipal wastewater reclamation: Membrane autopsy results from pilot-scale investigations. *J. Membr. Sci.* **2010**, *353* (1), 111−121.

(37) Melián-Martel, N.; Sadhwani, J.; Malamis, S.; Ochsenkuhn-Petropoulou, M. Structural and chemical characterization of long-term reverse osmosis membrane fouling in a full scale desalination plant. *Desalination* **2012**, *305*, 44−53.

(38) Ruiz-García, A.; Melián-Martel, N.; Mena, V. Fouling characterization of RO membranes after 11 years of operation in a brackish water desalination plant. *Desalination* **2018**, *430*, 180−185.

(39) Jafari, M.; Vanoppen, M.; van Agtmaal, J. M. C.; Cornelissen, E. R.; Vrouwenvelder, J. S.; Verliefde, A.; van Loosdrecht, M. C. M.; Picioreanu, C. Cost of fouling in full-scale reverse osmosis and nanofiltration installations in the Netherlands. *Desalination* **2021**, *500*, 114865.

(40) Flemming, H.-C. Biofouling and me: My Stockholm syndrome with biofilms. *Water research* **2020**, *173*, 115576.

(41) Antony, A.; Low, J. H.; Gray, S.; Childress, A. E.; Le-Clech, P.; Leslie, G. Scale formation and control in high pressure membrane water treatment systems: a review. *Journal of membrane science* **2011**, *383* (1), 1−16.

(42) Kang, G.-d.; Cao, Y.-m. Development of antifouling reverse osmosis membranes for water treatment: a review. *Water research* **2012**, *46* (3), 584−600.

(43) Goh, P.; Lau, W.; Othman, M.; Ismail, A. Membrane fouling in desalination and its mitigation strategies. *Desalination* **2018**, *425*, 130−155.

(44) Jiang, S.; Li, Y.; Ladewig, B. P. A review of reverse osmosis membrane fouling and control strategies. *Science of The Total Environment* **2017**, *595*, 567−583.

(45) Anis, S. F.; Hashaikeh, R.; Hilal, N. Reverse osmosis pretreatment technologies and future trends: A comprehensive review. *Desalination* **2019**, *452*, 159−195.

(46) Tang, F.; Hu, H.-Y.; Sun, L.-J.; Sun, Y.-X.; Shi, N.; Crittenden, J. C. Fouling characteristics of reverse osmosis membranes at different positions of a full-scale plant for municipal wastewater reclamation. *Water research* **2016**, *90*, 329−336.

(47) Boettcher, S. J.; Gately, C.; Lizano, A. L.; Long, A.; Yelvington, A. Part 3: Case Study Appendices to the Technical Reports. *EENRS Program Reports & Publications. 8*; 2020. DOI: 10.37419/EENRS.BrackishGroundwater.P3.

(48) Mukhopadhyay, D. Method and apparatus for high efficiency reverse osmosis operation. U.S. Patent No. 6537456, 2003.

(49) Tong, T.; Elimelech, M. The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environ. Sci. Technol.* **2016**, *50* (13), 6846−6855.

(50) Oren, Y.; Korngold, E.; Daltrophe, N.; Messalem, R.; Volkman, Y.; Aronov, L.; Weismann, M.; Bouriakov, N.; Glueckstern, P.; Gilron, J. Pilot studies on high recovery BWRO-EDR for near zero liquid discharge approach. *Desalination* **2010**, *261* (3), 321−330.

(51) Juby, G.; Zacheis, A.; Shih, W.; Ravishanker, P.; Mortazavi, B.; Nusser, M. D. Eastern Municipal Water District and Carollo Engineers. *Evaluation and Selection of Available Processes for a Zero-Liquid Discharge System for the Perris, California, Ground Water Basin.* DWPR No. 149; U.S. Department of the Interior, Bureau of Reclamation: Denver, CO, 2008.

(52) Shi, W.; Benjamin, M. M. Fouling of RO membranes in a vibratory shear enhanced filtration process (VSEP) system. *J. Membr. Sci.* **2009**, *331*, 11−20.

(53) Lozier, J. C.; Erdal, U. G.; Lynch, A. F.; Schindler, S. *Evaluating Traditional and Innovative Concentrate Treatment and Disposal Methods for Water Recycling at Big Bear Valley, California*; 2007.

(54) Enzweiler, R. J. Energy-Efficient Process for Using Membrane Technology to Treat and Recycle Agricultural Drainage Water. *Feasability Analysis and Final ESIG Report*; Report Number CEC-500-2005-092; California Energy Commission, 2005.

(55) Cappelle, M. A. High Recovery Inland Desalination: A Technical and Economic Performance Evaluation of Zero Discharge

https://doi.org/10.1021/acsestengg.1c00326
ACS EST Engg. XXXX, XXX, XXX−XXX

Desalination and Other Technologies. Ph.D. Thesis, University of Texas at El Paso, 2018.

(56) Warsinger, D. M.; Tow, E. W.; Nayar, K. G.; Maswadeh, L. A. Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination. *Wat. Res.* **2016**, *106*, 272−282.

(57) Erlitzki, R. High-Recovery Desalination to the Rescue: Making an Alternative Water Resource a Reality. Presented at *Multi State Salinity Coalition Annual Salinity Summit*, Las Vegas, NV, February 26−28, 2020. Available at: https://www.multi-statesalinitycoalition.com/past-mssc-summits/ (accessed 2021-09-08).

(58) Shubert, R. A. El Paso Water Utilities Board. Overview of the El Paso Kay Bailey Hutchison Desalination Plant. Presented at *Texas Desal Conference*, Austin, TX, September 30−October 1, 2015. Available at: http://www.texasdesal.com/wp-content/uploads/2016/02/Alan_Shubert.pdf (accessed 2021-09-08).

(59) Xu, P.; Cath, T. Y.; Wang, G.; Drewes, J. E. Critical Assessment of Implementing Desalination Technologies. Published by Water Research Foundation. 2009. Available at: https://www.sfwmd.gov/sites/default/files/documents/criicalassessmentimplemdesaltech.pdf (accessed 2021-09-08).

(60) Medina, V. F.; Johnson, J. L.; Waisner, S. A.; Wade, R.; Mattei-Sosa, J. Development of a treatment process for electrodialysis reversal concentrate with intermediate softening and secondary reverse osmosis to approach 98-percent water recovery. *J. Environ. Eng.* **2015**, *141* (7), 04015002.

(61) Miara, A.; Talmadge, M.; Sitterley, K.; Evans, A.; Huang, Z.; Macknick, J.; McCall, J.; Kurup, P.; Akar, S.; Van Allsburg, K. *The Water Technoeconomic Assessment Pipe-Parity Platform (WaterTAP3)*; National Renewable Energy Lab (NREL): Golden, CO (United States), 2021.

(62) Loh, H.; Lyons, J.; White, C. W. *Process equipment cost estimation, final report*; National Energy Technology Lab (NETL): Morgantown, WV (United States), 2002.

(63) Kappes, D. W. Precious metal heap leach design and practice. *Proceedings of the Mineral Processing Plant Design, Practice, and Control* **2002**, *1*, 1606−1630.

(64) Lu, Y.-Y.; Hu, Y.-D.; Zhang, X.-L.; Wu, L.-Y.; Liu, Q.-Z. Optimum design of reverse osmosis system under different feed concentration and product specification. *Journal of membrane science* **2007**, *287* (2), 219−229.

(65) Mickley, M. Membrane Concentrate Disposal: Practices and Regulation. *Desalination and Water Purification Research and Development Program Report No. 123*; 2007.

(66) McGivney, W.; Kawamura, S. *Cost estimating manual for water treatment facilities*; Wiley Online Library, 2008.

(67) Mickley, M. *Survey of high-recovery and zero liquid discharge technologies for water utilities*; WateReuse Foundation, 2008.

(68) Minnesota Department of Health and Minnesota Rural Water Association. *Minnesota Water Works Operations Manual* **2009**, 1−18.

(69) Plappally, A. Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable Sustainable Energy Rev.* **2012**, *16* (7), 4818−4848.

(70) Baker, R. W. *Membrane technology and applications*; John Wiley & Sons, 2012.

(71) He, Q. C.; Chiu, C.-A.; Lesan, D. User's Manual for Integrated Treatment Train Toolbox-Potable Reuse (IT3PR) Version 2.0; 2016.

(72) Voutchkov, N. *Desalination Project Cost Estimating and Management*; CRC Press, 2018.

(73) Mundy, B.; Kuhnel, B.; Hunter, G.; Jarnis, R.; Funk, D.; Walker, S.; Burns, N.; Drago, J.; Nezgod, W.; Huang, J. A review of ozone systems costs for municipal applications. Report by the municipal committee-ioa pan American group. *Ozone: Sci. Eng.* **2018**, *40* (4), 266−274.

(74) Bartholomew, T. V.; Mauter, M. S. Computational framework for modeling membrane processes without process and solution property simplifications. *J. Membr. Sci.* **2019**, *573*, 682−693.

(75) Bukhary, S.; Batista, J.; Ahmad, S. An analysis of energy consumption and the use of renewables for a small drinking water treatment plant. *Water* **2020**, *12* (1), 28.

(76) Amaya, M.; Mohamed, M.; Pingitore, N.; Aldouri, R.; Benedict, B. Community exposure to nighttime heat in a desert urban setting, El Paso, Texas. *Int. J. Adv. Remote Sensing GIS* **2016**, *5* (1), 1507−1513.

(77) Ghebreyesus, D.; Sharif, H. O. Time Series Analysis of Monthly and Annual Precipitation in The State of Texas Using High-Resolution Radar Products. *Water* **2021**, *13* (7), 982.

(78) Gooch, T.; Griffin, S.; Mullican, W. F., III. Texas Statewide Water Planning: The Regional Water Planning Concept. *Critical transitions in water and environmental resources management : Proceedings of the World Water and Environmental Resources Congress*, June 27−July 1, 2004, Salt Lake City, UT; American Society of Civil Engineers, pp 1−10

(79) Tarquin, A. J.; Fahy, M. P.; Balliew, J. E. Concentrate volume reduction research in El Paso, Texas. *World Environmental and Water Resources Congress 2010: Challenges of Change*; 2010; p 3507. .

(80) Campos, I.; Guemez, S.; Arevalo, J.; Brown, D.; Trejo, G. Life in the Desert Leads to Improvements at El Paso Water's Kay Bailey Hutchison Inland Desalination Plant. *Opflow* **2020**, *46* (12), 24−27.

(81) Reinert, S.; Klaes, B. Future Plant Improvements at the Kay Bailey Hutchison Desalination Plant - El Paso, TX. Presented at the *Multi State Salinity Coalition Annual Conference*, Las Vegas, NV, February 28−March 1, 2019. Available at: https://www.multi-statesalinitycoalition.com/past-mssc-summits/ (accessed 2021-09-08).

(82) Arroyo, J.; Shirazi, S. Cost of Brackish Groundwater Desalination in Texas. *Innovative Water Technologies*; Texas Water Development Board, 2012.

(83) He, C. Q.; Bond, R. G. *M69 Inland Desalination and Concentrate Management*, 1st ed.; American Water Works Association, 2019.

(84) Archuleta, E. G. *Desalination Concentrate Management Policy Analysis for the Arid West*; WateReuse Research Foundation, 2015.

(85) Wallace, P.; Ruiz, A. *Full Recovery Desalination*; AMTA/SCMA Joint Technology Transfer Workshop, El Paso, TX, 2018.

(86) Kolenc, V. Florida firm plans to mine minerals by reviving failed El Paso brine treatment plant: Critical Materials Corp., plans to mine brine to make chemicals for oil industry, fertilizer for agriculture, clean water for El Paso. *El Paso Times*; April 21, 2021. Avaialble at: https://www.elpasotimes.com/story/news/local/el-paso/2021/04/21/florida-firm-plans-to-mine-el-paso-salt-water-by-reviving-brine-plant/7256642002/ (accessed 2021-09-08).

(87) *EPW, Staff Report*. El Paso Water awarded $2.05m grant to expand Hutchison Desalination Plant. 2020. https://elpasoheraldpost.com/el-paso-water-awarded-2-05m-grant-to-expand-kay-bailey-hutchison-desalination-plant/ (accessed 2021-09-08).

(88) EMWD, Eastern Municipal Water District. Desalination Program. Available at: https://www.emwd.org. 2018. (accessed 2021-09-08).

(89) Juby, G.; Zacheis, A.; Shih, W.; Ravishanker, P.; Mortazavi, B.; Nusser, M. D. Evaluation and Selection of Available Processes for a Zero-Liquid Discharge System for the Perris, California, Ground Water Basin. *Desalination and Water Purification Research and Development Program Report No. 149*; U.S. Department of the Interior Bureau of Reclamation, 2008.

(90) Cerna, M. *Menifee and Perris I Desalters: Membrane Replacement Project*; Eastern Municipal Water District., 2017.

(91) EMWD, Eastern Municipal Water District. West San Jacinto Groundwater Management Area 2017 Annual Report. Accessed at: https://www.emwd.org/sites/main/files/file-attachments/westsanjacinto2017annualre.pdf. 2018. (accessed 2021-09-08).

(92) Jones, P. D. *Brackish Desalination - Water Supply Planning for Resiliency and Growth*; Eastern Municipal Water District, 2017.

(93) Nichols, T. *Inland Empire Interceptor Appraisal Analysis. Santa Ana Watershed Basin Study, CaliforniaLower Colorado Region*; Bureau of Reclamation. Engineering Services Office. Lower Colorado Regional Office, LC-6000. Technical Memorandum No. 3.0; Available at: https://www.usbr.gov/lc/socal/basinstudies/OWOWReferences/FinalReport/TM%203%20IEI%20AA.pdf. 2013. (accessed 2021-09-08).

(94) Girvin, P.; Graham Juby Wall, J. *EDR AquaSelTM Brine Concentration Pilot Project Update*; Eastern Municipal Water District, 2016.

(95) Owens-Bennett, E.; Trussell, B.; Monroy, I.; Trussell, R. *Proposed solids formation recovery formula for the inland empire brine line*; Santa Ana Watershed Project Authority: Riverside, CA, 2016.

(96) Tang, X.; Kum, S.; Liu, H. Inland Desalination Brine Disposal: A Baseline Study from Southern California on Brine Transport Infrastructure and Treatment Potential. *ACS ES&T Eng.* **2021**, DOI: 10.1021/acsestengg.1c00276.

(97) Ghaderi, K.; Reeve, M.; Juby, G. AquaSelTM Technology Pilot-Scale Demonstration Menifee Desalter. *Bureau of Reclamation Desalination and Water Purification Research and Development Report No. 195*; 2016.

(98) *EMWD Receives $25M Federal Authorization for South Perris Desalination Program*; EMWD, Eastern Municipal Water District, 2021.

(99) Pickard, B.; Bari, M. Feasibility of Water Treatment Technologies for Arsenic and Fluoride Removal from Groundwater. Presented at the *AWWA Water Quality Technology Conference*, San Antonio, TX, 2004.

(100) USEPA, United States Environmental Protection Agency. The Arsenic Rule: Background and Rule Provisions. Accessed at: https://www.epa.gov/sites/production/files/2015-09/documents/train1-background.pdf. 2006. (accessed 2021-09-08).

(101) Alborzfar, M.; Cox, E. Providing Quality Water to Our Customers: Pilot Testing of EDR for Fluoride, Arsenic, and TDS Removal at Fort Irwin, California. Presented at *AWWA Membrane Technology Conference and Exposition (2007)*, American Water Works Association, March 18−21, 2007. Tampa, FL, 2007.

(102) CH2M, Fort Irwin Water Treatment Process Selection Based on Pilot Testing Results. CH2M HILL. 2006.

(103) Mickley, M. Updated and Extended Survey of US Municipal Desalination Plants; 2018.

(104) CRWQC, California Regional Water Quality Control Board - Lahontan Region. *Meeting of February 11, 2015 Apple Valley, CA. Board Order No. R6V-2015-(PROPOSED). WDID No. 6B361409017.* New Waste Discharge Requirements Fort Irwin U.S. Army National Training Center, Irwin Water Works. San Bernardino County. Accessed: https://www.waterboards.ca.gov/lahontan/board_info/agenda/2015/feb/item_6.pdf. 2015. (accessed 2021-09-08).

(105) Lakretz, A.; Adler, M.; Orly, E.; Priel, M. Lahat BWRO plant: technical and economic evaluation of energy recovery alternatives. *Desalin. Water Treat.* **2015**, *55* (11), 3040−3047.

(106) Staff, A. *Electrodialysis and Electrodialysis Reversal (M38)*; American Water Works Association, 1996.

(107) Ziolkowska, J. R.; Reyes, R. Prospects for desalination in the United States—Experiences from California, Florida, and Texas. In *Competition for Water Resources*; Elsevier: 2017; pp 298−316.

(108) Mace, R. E.; Nicot, J.-P.; Chowdhury, A. H.; Dutton, A. R.; Kalaswad, S. Please pass the salt: Using oil fields for the disposal of concentrate from desalination plants. *Texas Water Development Board Report* **2006**, *366*, 198.

(109) Wang, Z.; Chen, G.; Patton, S.; Ren, C.; Liu, J.; Liu, H. Degradation of nitrilotris-methylenephosphonic acid (NTMP) antiscalant via persulfate photolysis: Implications on desalination concentrate treatment. *Water research* **2019**, *159*, 30−37.

(110) Duff, J.; LaBate, V.; Slugg, A. M. Prospects and Pitfalls of Desalination Development: Insights from Three States. *Ocean Coastal Law J.* **2017**, *22*, 130.

(111) Greenlee, L. F.; Testa, F.; Lawler, D. F.; Freeman, B. D.; Moulin, P. Effect of antiscalants on precipitation of an RO concentrate: metals precipitated and particle characteristics for several water compositions. *Water research* **2010**, *44* (8), 2672−2684.

(112) Jain, T.; Sanchez, E.; Owens-Bennett, E.; Trussell, R.; Walker, S.; Liu, H. Impacts of antiscalants on the formation of calcium solids: Implication on scaling potential of desalination concentrate. *Environmental Science: Water Research & Technology* **2019**, *5* (7), 1285−1294.

(113) McCool, B. C.; Rahardianto, A.; Cohen, Y. Antiscalant removal in accelerated desupersaturation of RO concentrate via chemically-enhanced seeded precipitation (CESP). *Water research* **2012**, *46* (13), 4261−4271.

(114) Semblante, G. U.; Lee, J. Z.; Lee, L. Y.; Ong, S. L.; Ng, H. Y. Brine pre-treatment technologies for zero liquid discharge systems. *Desalination* **2018**, *441*, 96−111.

(115) Greenlee, L. F.; Testa, F.; Lawler, D. F.; Freeman, B. D.; Moulin, P. Effect of antiscalant degradation on salt precipitation and solid/liquid separation of RO concentrate. *J. Membr. Sci.* **2011**, *366* (1−2), 48−61.

(116) Alabi, A.; Chiesa, M.; Garlisi, C.; Palmisano, G. Advances in anti-scale magnetic water treatment. *Environmental Science: Water Research & Technology* **2015**, *1* (4), 408−425.

(117) Demopoulos, G. Aqueous precipitation and crystallization for the production of particulate solids with desired properties. *Hydrometallurgy* **2009**, *96* (3), 199−214.

(118) Chen, T.; Neville, A.; Yuan, M. Calcium carbonate scale formation—assessing the initial stages of precipitation and deposition. *J. Pet. Sci. Eng.* **2005**, *46* (3), 185−194.