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Technoeconomic Framework for Evaluating Desalination and Brine Management Pathways across the United States

Akanksha Menon

amenon84@gatech.edu

Georgia Institute of Technology https://orcid.org/0000-0003-1979-507X

Walter Parker

Georgia Institute of Technology

Jordan Kocher

National Laboratory of the Rockies

Analysis

Keywords: Zero Liquid Discharge, Levelized Cost of Water, Brine Management, Technoeconomic Analysis, Circular Water Economy

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Technoeconomic Framework for Evaluating Desalination and Brine Management Pathways across the United States

Walter P. Parker Jr.[1], Jordan D. Kocher[1], and Akanksha K. Menon[1*]

[1] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

[*] Corresponding author: akanksha.menon@me.gatech.edu

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Abstract

The growth of desalination capacity to address global water stress has intensified the need for effective and economically viable brine management strategies. This work develops a geospatial technoeconomic analysis framework for freshwater production using desalination (via reverse osmosis) with brine management across the United States. Levelized cost of water (LCOW) is used to determine the most viable brine management approach as a function of geographic location, feed salinity, transport distance, and revenue from salt recovery. The results show that ocean discharge (OD) is the most favorable brine management strategy across most of the country owing to its relatively low disposal cost, particularly in coastal regions where seawater (SW) desalination has LCOW values between 1–1.5 $/m³. However, transport costs increase substantially with distance from the coast, making desalination of alternate feed sources such as brackish groundwater (BGW) and produced water (PW) more practical. For low salinity BGW feed, zero liquid discharge (ZLD) is generally not economically competitive because limited salt recovery cannot offset the high capital and operating costs associated with brine concentration (mechanical vapor compression or MVC) and crystallization (evaporation pond or EP) systems. In contrast, PW feed with higher salinity favors ZLD due to increased salt recovery potential. A sensitivity analysis further reveals that feed/brine transport cost has the largest impact on LCOW, while ZLD equipment cost and salt revenue become increasingly important for higher-salinity feed. These results are used to develop a regime map that identifies the economically preferred brine management pathway as a function of feed salinity and distance from the coast, thereby providing a generalized decision-making tool for implementation across the United States.

Main

Global water scarcity has intensified over recent decades due to rapid population growth, urbanization, industrial expansion, and agricultural demand. Freshwater withdrawals have increased nearly six-fold since 1900, with the most significant increases occurring after the 1950s as economic development and food production increased worldwide[1-6]. Agriculture remains the dominant consumer of freshwater resources, accounting for approximately 70% of global withdrawals, while industrial activities contribute nearly 20% and municipal use is approximately 12%[3,4,7]. Simultaneously, population growth and climate change have intensified regional water stress, particularly in arid and inland regions where freshwater supplies are limited. Current estimates indicate that nearly half of the global population experiences severe water scarcity for at least a part of the year[5,7]. As conventional freshwater resources become increasingly depleted, technologies using nontraditional water resources such as brackish groundwater and produced water desalination, municipal wastewater treatment, and atmospheric water harvesting have emerged to match water supply with demand[1,2,8-10].

Among these alternative approaches, desalination is the fastest growing water treatment technology worldwide. Advances in membrane technology, and energy recovery devices have enabled rapid expansion of desalination infrastructure over the past two decades[10-12]. Global desalination capacity has increased from approximately 32 million m³/day in 2000 to more than 120 million m³/day to address water scarcity[13-15]. Reverse osmosis (RO) is the dominant desalination technology for seawater (SW) due to its lower energy requirements compared to thermal desalination systems[9,10,16]. The rapid increase in desalination deployment has resulted in a substantial increase in brine production that requires effective disposal or management strategies. Global brine production is estimated to be 142 million m³/day, which exceeds the total freshwater production[13,17,18]. The brine is at elevated salinity levels and contains treatment chemicals, heavy metals, and other contaminants that can negatively impact surrounding environments if improperly managed[19,20]. Current brine disposal methods consist of ocean discharge (OD) for coastal desalination facilities and deep well injection (DWI) for inland desalination systems. Ocean discharge relies on

dilution and dispersion into marine environments, whereas DWI injects brine into deep geological formations underground. Both methods introduce economic, environmental, and regulatory concerns that become increasingly important as desalination infrastructure expands. [21-23].

Zero liquid discharge (ZLD) is an alternative brine management approach for inland desalination that maximizes freshwater recovery while transforming brine into salt and other minerals[24-29]. ZLD systems are comprised of a series of treatment processes following the primary desalination technology (generally RO), including a brine concentrator which recovers up to 80-90% of the water (minimal liquid discharge or MLD)[25,30-33], followed by a brine crystallizer (e.g., passive evaporation pond). However, these systems are often associated with high energy consumption and operational costs, as well as significant capital investments[24,28,31,34-38]. Atmospheric water harvesting (AWH) is an alternative freshwater production approach in which water is directly extracted from the atmosphere rather than a saline source[8,39-42]. However, the performance of these devices is highly dependent on the local climate conditions (humidity and temperature), and the more dilute separation requires significantly higher specific energy consumption compared to desalination[8].

In the United States, Brackish groundwater (BGW) represents the largest feed source, accounting for approximately 65-70% of desalinated water production, followed by SW at 10-15%, and produced water (PW) at less than 5%[43-45]. Despite this, desalination contributes only a small fraction of the total freshwater supply, with approximately 99% originating from conventional surface water and fresh groundwater sources, [46,47]. As water scarcity intensifies and conventional freshwater resources become increasingly constrained, BGW and PW represent an opportunity to expand freshwater supplies through inland desalination[48-53]. These sources can reduce dependence on coastal desalination infrastructure and improve freshwater accessibility in water-stressed regions[54]. The USGS estimates that substantial unconventional water resources are available throughout the United States, including widespread brackish groundwater resources characterized using geochemical data from over 300,000 groundwater wells and extensive produced water resources associated with oil and gas operations nationwide. These datasets highlight the significant potential of BGW and PW as alternative feedwater sources for desalination and water reuse applications, as shown in Fig. 1[55-59]. However, each source introduces unique water quality characteristics, treatment requirements, recovery limitations, and brine disposal constraints[48,60,61]. As a result, the feasibility and cost-effectiveness of brine management strategies differ substantially depending on the water source and geographic location. Studies in literature have evaluated brine management technologies and economics, but they do not examine the effect of different feed sources, geographic locations, or population resulting in an important aspect missing in literature[24,25,31,35,62,63].

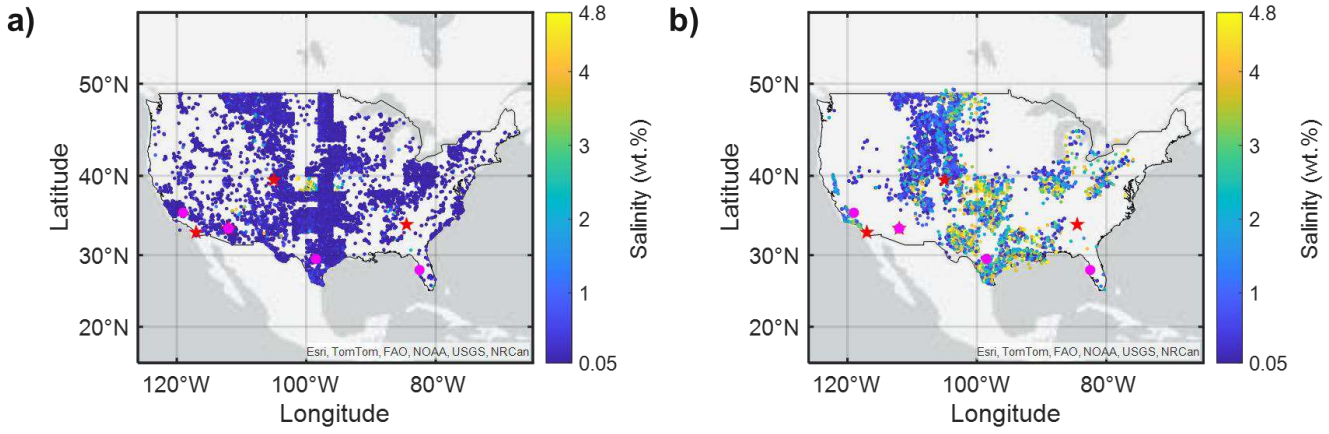


Fig. 1. Spatial distribution and salinity of **a)** brackish ground water and **b)** produced water feed sources across the continental United States. The case study locations are also shown on both maps – for seawater, the cities are San Diego, Denver, Phoenix and Atlanta (red stars); for brackish ground water and produced water, the cities are Bakersfield, Tampa Bay, Phoenix, and San Antonio (magenta circles).

In our previous work, we performed a global analysis of SWRO desalination and AWH systems to compare their energy efficiency (kWh/m^3) and levelized cost ($/m^3) at different water-stressed locations[8]. The main takeaway from this paper is that AWH is generally far more energy-intensive and costly than coastal seawater desalination combined with inland water transport, making it an impractical solution for a large portion of the global population. However, AWH can serve as a viable, lowest-cost niche option specifically for sorbent-based water extraction in highly arid

regions located far from the coast[8]. However, this analysis did not incorporate alternative feed sources (PW and BGW) or brine disposal strategies to evaluate how that impacts overall feasibility and cost.

This work presents a unified framework to evaluate desalination of three distinct water resources, across multiple brine management approaches to determine the most cost-effective desalination and brine management strategies. By incorporating geographic variability, feedwater composition (salinity), population distribution, and transportation distance, this work aims to identify how optimal desalination and brine management approaches vary spatially to address water stress across the United States.

Overview of Brine Management

Three feed sources were considered, including seawater (SW), brackish ground water (BGW), and produced water (PW). For each of these saline sources, the primary desalination approach was either seawater reverse osmosis (SWRO) or brackish water reverse osmosis (BWRO). SWRO was used for coastal seawater desalination with an inlet salinity of 3.5 wt.%. For BGW and PW sources, the desalination approach varied between BWRO and SWRO (or a combination of both) depending on the feed salinity and brine disposal approach. Specifically, BWRO was used as the initial desalination technology for feed salinities between 0.05 and 1.2 wt.%, whereas SWRO was used for feed salinities greater than 1.2 wt.% and up to 4.8 wt.%.

The brine from RO was managed using different approaches, including ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD), as shown in Fig. 2a to determine the most cost-effective method. For SW, two brine management approaches were used, as shown in Fig. 2b and 2c. This includes OD (7 wt.% brine from the coastal RO plant is discharged into the ocean, and the freshwater is transported to the desired location) and ZLD (brine is further concentrated) using mechanical vapor compression (MVC) to extract more water up to a brine salinity of 20 wt.%, followed by an evaporation pond (EP) that takes the brine up to saturation (~26 wt.%). For the ZLD configuration, freshwater from RO and MVC is transported to the desired location, while the salt from the EP is valorised to offset the cost of the additional ZLD equipment.

For BGW (0.05 – 1.2 wt.%) and PW (>1.2 – 4.8 wt.%), three brine management approaches were analysed, as shown in Fig. 2d – 2f. This includes OD (brine from the inland RO plant is transported to the ocean), DWI (brine is disposed underground), and ZLD (brine is concentrated up to saturation to recover salts). A detailed breakdown of the desalination and brine management approach is provided in the Method section and Supplementary Note S1.

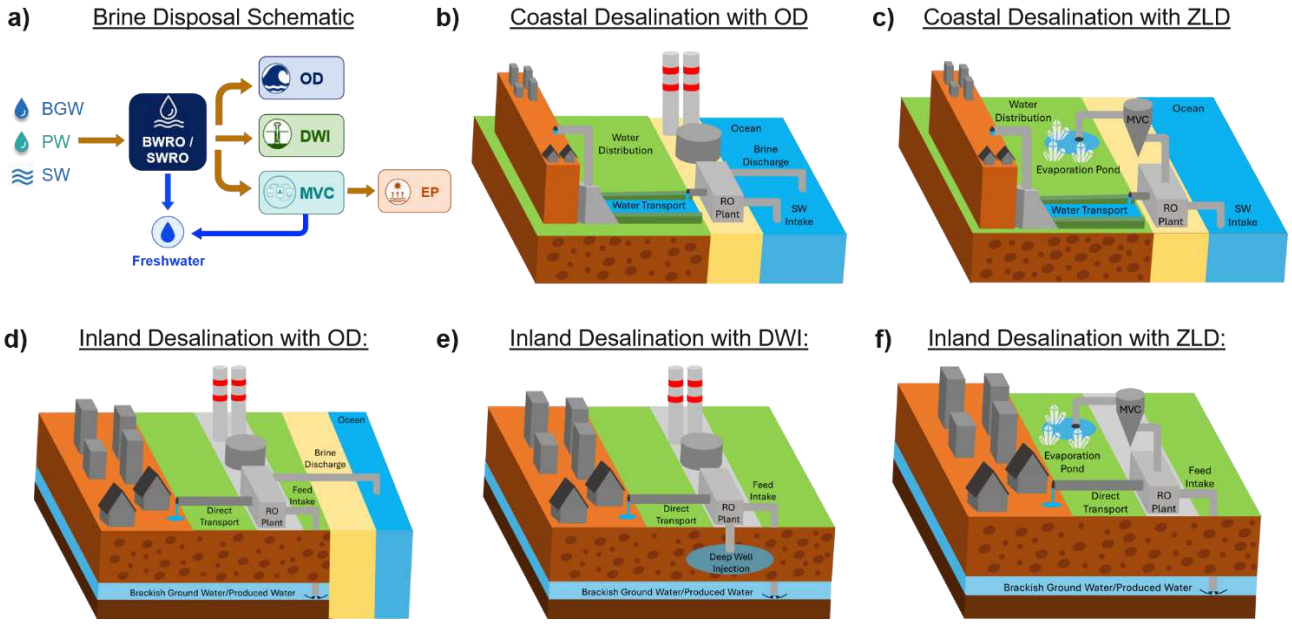


Fig. 2. Schematics of the brine disposal pathways evaluated for seawater (SW), brackish groundwater (BGW), and produced water (PW) desalination. **(a)** Overall schematic illustrating the brine management pathways following BWRO/SWRO treatment, which includes ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD) using mechanical vapor compression (MVC) and evaporation ponds (EP). **(b)** Coastal SW desalination with brine disposal via ocean discharge and freshwater transport inland. **(c)** Coastal SW desalination with ZLD, where brine is treated using MVC and EP for salt recovery. **(d)** Inland desalination of BGW and PW with brine disposal to the coast via ocean discharge. **(e)** Inland desalination of BGW and PW with brine disposal via deep well injection. **(f)** Inland desalination of BGW and PW with ZLD for salt recovery.

To determine the most cost-effective (optimal) approach for each feed, a technoeconomic analysis was performed that calculates the levelized cost of water (LCOW) for every location within the continental United States.

The LCOW for each desalination technology and brine management approach was calculated in units of $/m³ (normalized to the volume of freshwater produced). The LCOW framework incorporates the lifetime capital expenditures and operating expenditures, as well as energy costs, associated with each desalination and brine disposal strategy over the operational lifetime of the system. The LCOW for each desalination and brine disposal strategy was calculated using Eq. (1):

$$LCOW = \left(\sum_i \frac{CAPEX_i \times \frac{r(1+r)^{n_i}}{(1+r)^{n_i}-1} \times RR_i}{365 * RR_{total}} + OPEX_{fix,i} + OPEX_{var,i} \right) + OPEX_{repl} + OPEX_{trans} - OPEX_{SS} \quad (1)$$

The first term represents the amortized capital expenditure associated with the desalination system. Within this, CAPEX is the capital cost of the desalination system in units of $/(m³/day), *r* is the discount rate, *n* is the lifetime of the desalination technology, RR is the water recovery ratio of the desalination system, and RR_{total} is the overall water recovery ratio of the combined desalination and brine management system. The $OPEX_{fix}$ term ($/m³) represents the fixed operations and maintenance costs, while $OPEX_{var}$ ($/m³) corresponds to the variable operating costs, which are primarily governed by the energy consumption of the desalination and brine concentration systems. For BGW and PW feeds (treated as ideal solutions), the specific energy consumption (SEC) of the RO and MVC system was calculated using the exergetic efficiency and the minimum work of separation for finite recovery. It should be noted that real brines may deviate from ideal solution behavior as salinity increases, which in turn will result in a higher SEC and LCOW compared to the results shown in this work. Details on the energy calculations for each desalination technology are provided in Supplementary Note S3. The $OPEX_{repl}$ term ($/m³) accounts for membrane replacement costs associated with the RO system. The $OPEX_{trans}$ term ($/m³) represents transport costs, including the transport of freshwater to the target location after desalination, transport of brine from inland desalination to the coast via OD, and/or the transport of BGW and PW feed to the desalination facility. The final term in Eq. (1), $OPEX_{SS}$ ($/m³), represents the revenue generated from the sale of salts recovered through ZLD. The input parameters used for this analysis can be found in Supplementary Note S2. The terms in Eq. (1) were adjusted according to the process configuration by incorporating the recovery factor, defined as RR to RR_{total}. Additional details on the derivation of the final LCOW expressions for each desalination and brine disposal configuration are provided in Supplementary Note S4.

Additionally, case studies were performed in selected cities to provide a more in-depth cost analysis. For the SW case study, the four cities selected were San Diego, CA; Denver, CO; Phoenix, Arizona; and Atlanta, GA based on their water stress and varying distances from the coast. For the BGW and PW case studies, the four cities selected were San Antonio, TX; Tampa Bay, FL; Bakersfield, CA; and Phoenix, AZ based on their use of these alternate feed sources to address water scarcity. The location of each city for the SW, BGW, and PW desalination case studies is shown in Fig. 1.

Results

Seawater Desalination for Coastal Freshwater Production

The LCOW was evaluated spatially across the United States for coastal seawater reverse osmosis (SWRO) desalination coupled with either ocean discharge (OD) or zero liquid discharge (ZLD) brine management strategies. For both OD and ZLD, SWRO had a SEC of 5 kWh/m³ with a water recovery of 50%, while MVC had a SEC of 27 kWh/m³ and a water recovery of 65%. Finally, EP required no energy input and achieved 23% water removal. As expected, the results shown in Fig. 3a, using the baseline input parameters (Supplementary Note S2), indicate that coastal desalination with OD is consistently more economically favourable than ZLD (Each location is coloured only for the brine management approach that has the cheapest cost.). The primary reason for the higher LCOW associated with ZLD is the additional capital expenditure (CAPEX) and operational expenditure (OPEX) associated with MVC and EP components required for brine concentration and salt recovery. Although ZLD systems can generate revenue from the salt, the baseline price of 30 $/ton was insufficient to offset the additional treatment costs. A sensitivity analysis was performed to determine the salt selling price required to make ZLD competitive with ocean discharge. To reduce the overall LCOW, a salt price of approximately 49 $/ton is necessary for the revenue generated from

recovered salts to offset the increased CAPEX and OPEX associated with the MVC and EP systems to make ZLD more cost-effective than OD. While this suggests that ZLD for seawater desalination can become economically competitive, maintaining this salt price over the operational lifetime of a desalination facility is unlikely due to market volatility and regional demand limitations (e.g., significant mismatch in the amount of salt recovered from ZLD vs. what is needed in the chlor-alkali industry)[64-66]. As such, large-scale implementation of ZLD for seawater desalination is not a viable solution from a cost perspective.

For SWRO with OD, a case study was conducted for four U.S. cities (San Diego, Denver, Atlanta, and Phoenix) to evaluate the impact of distance from the coast on the overall LCOW. The results shown Fig. 3b reveal that freshwater transport is the primary factor influencing regional variation in LCOW. In San Diego, the LCOW was approximately 1.15$/m³, which aligns closely with reported values for the Carlsbad desalination plant (~1.5$/m³) and validates the developed technoeconomic model. The difference is likely attributable to differences in system boundaries, financial assumptions, and the inclusion of site-specific operating, maintenance, and infrastructure costs in the reported plant value. Nonetheless due to the city's proximity to the coastline, the freshwater transport contribution is nearly negligible at ~0.03 $/m³.

Given their relatively similar distances from coastal desalination facilities, Atlanta and Phoenix exhibited comparable transport costs of approximately 0.69 $/m³ and 0.71 $/m³, respectively. Although this increased the overall LCOW for these inland cities, the primary SWRO was the dominant cost contribution. In contrast, Denver exhibited a substantially larger transport cost of ~2.4 $/m³ because of its greater inland distance from coastal water sources and elevation. As a result, transport cost alone was more than double the SWRO treatment cost, yielding an overall LCOW of ~3.5 $/m³. This baseline analysis highlights that seawater desalination is cost-prohibitive for inland locations due to transport requirements. Alternative feed sources such as brackish groundwater (BGW) and produced water (PW) are more relevant, as discussed in the next section.

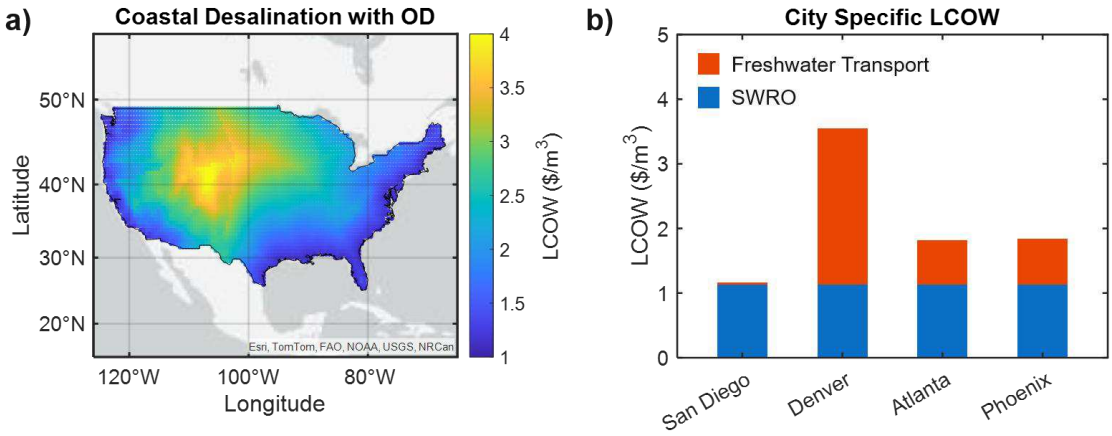


Fig. 3: **(a)** Levelized cost of water (LCOW) for coastal seawater reverse osmosis (SWRO) desalination with ocean discharge (OD) across the United States (the map is colored only in locations where OD has the cheapest cost relative to ZLD). **(b)** LCOW breakdown showing the contributions of SWRO treatment at the coast and freshwater transport costs for San Diego, Denver, Atlanta, and Phoenix.

Brackish and Produced Water Desalination for Freshwater Production Inland

The LCOW was evaluated spatially across the United States for inland BGW desalination coupled with brine management via ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD). Comparison of these three approaches indicates that OD is generally most cost-effective, followed by DWI, while ZLD is economically viable only in some locations, as shown in Fig. 4. Specifically, across all latitude and longitude points evaluated, OD was the preferred option for ~59% of the locations shown in Fig. 4a, whereas DWI and ZLD were preferred for ~35% and 6% of the locations, respectively.

As the distance from the coast increases, Fig. 4b shows that DWI becomes more cost-effective than OD, primarily because of the rising brine transport cost. In many inland regions, higher elevations further increase pumping and transport requirements, resulting in a higher overall LCOW. ZLD remained the least cost-effective of the three brine

management strategies, but it became economically favourable in select locations where distance from the coast made OD impractical and higher brackish groundwater salinities (salinity ranges were between 0.2 – 4.8 wt.%) increased the amount of salt recovered, as shown in Fig. 4c. The additional revenue generated from salt recovery helped offset the higher capital and operating costs associated with ZLD, thereby improving its economic viability

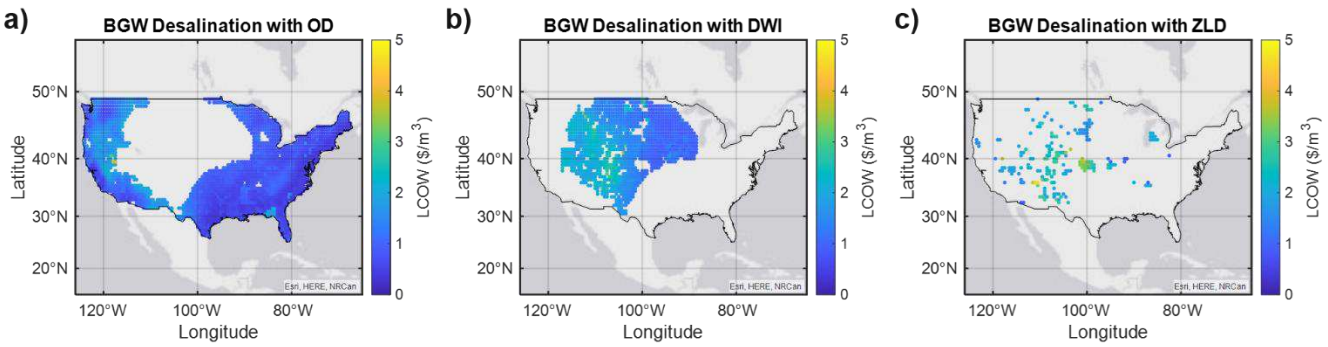


Fig. 4: Spatial distribution of the levelized cost of water (LCOW) for inland brackish groundwater (BGW) desalination across the United States using three brine management strategies: **(a)** ocean discharge (OD), **(b)** deep well injection (DWI), and **(c)** zero liquid discharge (ZLD).

In practice, many inland desalination facilities do not implement either OD or DWI and instead discharge brine into alternative waters, such as rivers or lakes, after blending to reduce salinity to acceptable levels. This approach is often more economically attractive than transporting brine to the coast or implementing DWI systems[18,23].

A case study was conducted for four cities (San Antonio, Tampa Bay, Bakersfield, and Phoenix) to better understand the economic contribution of each brine management strategy at the local scale. These cities were selected as they either currently implement BGW desalination or are considering it for freshwater production. As shown in Fig. 5, OD was the lowest-cost brine management strategy for all four cities with LCOW ranging between 0.53 – 1.18 $/m³. This is attributed to the relative proximity to the coast and/or to the low salinity of BGW that makes ZLD less favourable. The BWRO contribution to LCOW is relatively low for both the OD and DWI cases because of the comparatively low energy requirement (between 0.49 – 2.48 kWh/m³ at a recovery of 75%) associated with desalinating lower salinity feed. Transport costs can substantially influence the overall LCOW depending on the relative locations of the BGW source and the desalination plant. For example, feed transport in Tampa Bay was approximately 0.33 $/m³, which is comparable to the BWRO desalination cost (~0.34 $/m³). Similar trends were observed for Bakersfield and Phoenix, where feed transport costs were approximately two times greater than the BWRO contribution of 0.34 and 0.25 $/m³, respectively. Additionally, brine transport for the OD configuration contributed significantly to the overall LCOW, accounting for approximately 13% in Bakersfield, 25% in San Antonio, and 22% in Phoenix, whereas Tampa Bay had the lowest brine transport cost because of its proximity to the coast. For the DWI configuration, brine disposal cost represented a substantial fraction of the overall LCOW, contributing approximately 56% in San Antonio, 43% in Tampa Bay, 33% in Bakersfield, and 39% in Phoenix. Despite feed transport and brine disposal costs representing a significant portion of the total LCOW, the results still demonstrate that OD and DWI remain more economically favourable than ZLD for BGW desalination in the selected cities.

For the ZLD configuration, the BWRO cost contribution increases significantly because of the high-water recovery (94 – 98% water recovery) before the brine is transferred to the SWRO, MVC, and evaporation pond (EP) units downstream. Consequently, most of the energy consumption occurs within the BWRO system (10 – 15 kWh/m³ see Supplementary Note S6), leaving relatively low brine volume for the downstream components to treat. As shown in Fig. 5, the BWRO contribution accounts for most of the ZLD LCOW, representing approximately 65%–88% of the total system cost across the evaluated cities. In comparison, the combined SWRO, MVC, and EP contributions are relatively small, particularly for lower salinity feed. In all the cities, the downstream SWRO, MVC, and EP stages collectively contribute less than ~5% of the net LCOW.

Additionally, Fig. 5 illustrates that the salt revenue has only a small contribution (0.01 – 0.08 $/m³ for the cities evaluated) to offsetting the overall LCOW owing to the low salinity of BGW. This highlights the importance of both feed composition and salt market value when evaluating the economic feasibility of ZLD systems. If salt prices remain low, the financial benefit associated with salt recovery may be insufficient to offset the additional cost

associated with ZLD implementation. Additional analysis of BGW desalination and the effect of varying the salt selling price is provided in Supplementary Note S7.

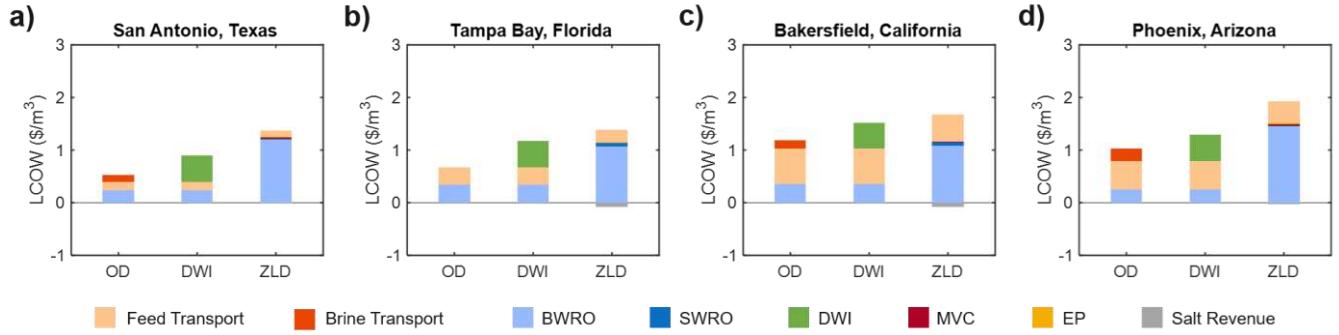


Fig. 5: Levelized cost of water (LCOW) breakdown for BGW desalination utilizing ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD) brine management strategies for four cities in the United States: **(a)** San Antonio, TX; **(b)** Tampa Bay, FL; **(c)** Bakersfield, CA; and **(d)** Phoenix, AZ.

In most desalination applications, SW or BGW are used as the primary feed for freshwater production. However, produced water (PW) has emerged as an alternative feed because it represents a relatively underutilized water resource. One of the primary challenges associated with PW desalination is the complex composition of the feed stream, which may contain constituents that promote scaling, fouling, and membrane clogging, in addition to salinity levels that can exceed the operating limits of conventional desalination systems[48,51,61,67,68]. In this study, the PW feed stream was simplified to a binary NaCl–water solution, and only sources within a salinity range of 0.05 wt. – 4.8 wt.% were considered for this analysis (see Methods section).

For PW desalination integrated with the three brine management strategies, Fig. 6 shows that OD and ZLD are the most economically favorable approaches, accounting for approximately 39% and 40% of the evaluated locations respectively (in coastal regions as shown in Fig. 6a, followed by DWI at 21% (in inland locations as shown in Fig. 6b). In contrast to the BGW case, ZLD becomes viable for PW (as shown in Fig. 6c) owing to the higher salinity that increases the amount of salt recovered, thereby contributing revenue to partially offset the LCOW.

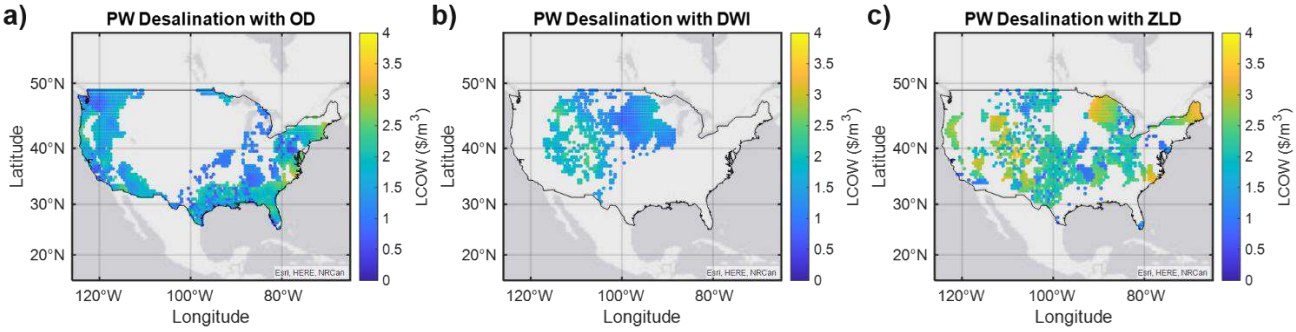


Fig. 6: Spatial distribution of the levelized cost of water (LCOW) for inland produced water (PW) desalination across the United States using three brine management strategies: **(a)** ocean discharge (OD), **(b)** deep well injection (DWI), and **(c)** zero liquid discharge (ZLD).

The same representative cities used in the BGW case study were further evaluated using PW as the feed source, as shown in Fig. 7. The results indicate that OD remained the lowest-cost brine management strategy for all cities considered. San Antonio exhibited the highest LCOW because of the elevated feed salinity (2.7 wt.%), whereas Bakersfield showed the lowest LCOW because it had the lowest salinity (0.1 wt.%) among the selected locations.

As shown in Fig. 7a, the ZLD configuration for San Antonio resulted in an LCOW that surpassed approximately 3 $/m³ but with the salt revenue the net LCOW reduces to 2.1 $/m³, which is cheaper than DWI (2.9 $/m³) but still more than OD (1.7 $/m³). In the ZLD case, the downstream SWRO, MVC, and EP units collectively accounted for over half of the total LCOW (with a total water recovery between 87 – 99% for all the cities), demonstrating how higher feed salinity significantly drives up treatment cost.

For Tampa Bay, Bakersfield, and Phoenix, the LCOW values for OD ranged between 0.7 – 1.4 $/m³, while the DWI cases were approximately 1 – 1.7 $/m³. The net LCOW (accounting for salt revenue) for the ZLD configuration in

these locations remained under ~2.2 $/m³, with the BWRO stage accounting for most of the system cost. For example, in Bakersfield and Phoenix, BWRO was ~60–80% of the net LCOW (with a water recovery of 96% and 83% for Bakersfield and Phoenix respectively), while the combined SWRO, MVC, and EP contributions were relatively small given the lower feed salinity in these locations, as was observed in the BGW case study. In addition, the salt revenue was negligible for the lower-salinity PW cases, making it insufficient to offset the additional costs associated with ZLD implementation. These findings emphasize that the economic feasibility of ZLD for PW desalination strongly depends on feed salinity, distance from the coast, and the market value of the recovered products. For high-salinity PW feeds such as in San Antonio, increased salt recovery and higher concentration duty make ZLD more economically relevant, whereas low-salinity PW feeds provide limited economic incentive for implementing ZLD. Additional analysis of the effect of varying the salt selling price on PW desalination is provided in Supplementary Note S7.

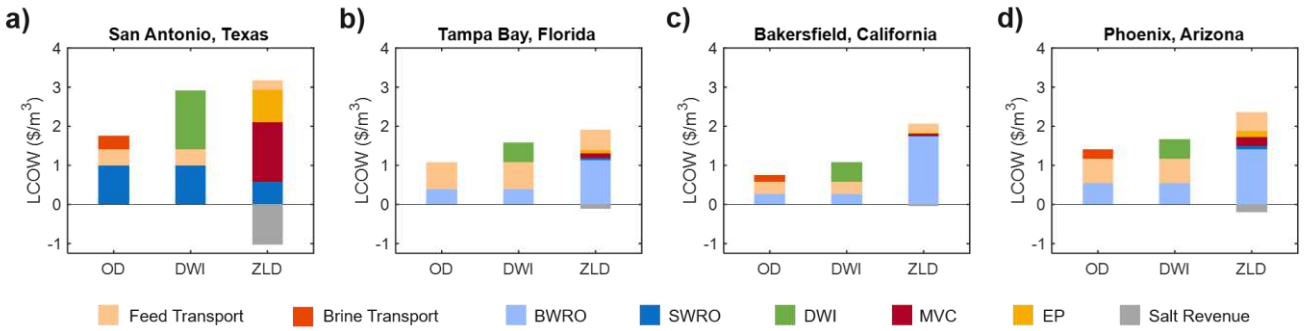


Fig. 7: Levelized cost of water (LCOW) breakdown for PW desalination systems utilizing ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD) brine management strategies for four cities in the United States: **(a)** San Antonio, TX; **(b)** Tampa Bay, FL; **(c)** Bakersfield, CA; and **(d)** Phoenix, AZ.

Sensitivity Analysis of Feed Source Cities

To better understand the LCOW trends observed in the selected cities and to evaluate the influence of economic assumptions, a sensitivity analysis was conducted to examine how variations in transport cost, salt selling price, and ZLD equipment cost impact net LCOW (see Table S2 in Supplementary Note S7). Among the three feed sources considered, PW desalination was most sensitive to these parameters, as shown in Fig. 8.

Across all evaluated cities for PW desalination, transport cost had the biggest impact on LCOW compared to variations in salt selling price and ZLD equipment cost (capex). For example, Tampa Bay showed maximum LCOW increases of only ~0.01 and 0.06 $/m³ with salt selling price and ZLD equipment cost, respectively. Similarly, Bakersfield and Phoenix showed ZLD equipment sensitivity increases in LCOW of only ~0.16 and 0.30 $/m³, respectively. This is consistent with previous results, as most of the water recovery for lower salinity feed occurs within the BWRO and/or SWRO units. Consequently, the downstream ZLD processes have only a limited effect on the net LCOW under these operating conditions.

The analysis also reveals that increasing the cost of these input parameters has a larger effect on LCOW than decreasing the same parameters by an equivalent amount. For example, increasing transport cost by a factor of five resulted in LCOW increases ranging from 0.95–3.44 $/m³ across the evaluated cities, whereas decreasing this cost by the same factor reduced LCOW by only ~0.19–0.69 $/m³ from the baseline value. Similar asymmetric trends were also observed for the ZLD equipment cost and salt selling price sensitivity. This is because reducing an already small contribution to LCOW provides only a limited reduction in the overall system cost, whereas increasing that contribution makes it account for a substantially larger fraction of net LCOW.

Overall, this sensitivity analysis provides insight into how uncertain economic assumptions may influence the LCOW of the evaluated desalination and brine management strategies. These results also help identify which parameters exert the greatest influence on system economics, and under what operating conditions they become significant. Additional details and results for the sensitivity analysis on other feed sources are provided in Supplementary Note S7.

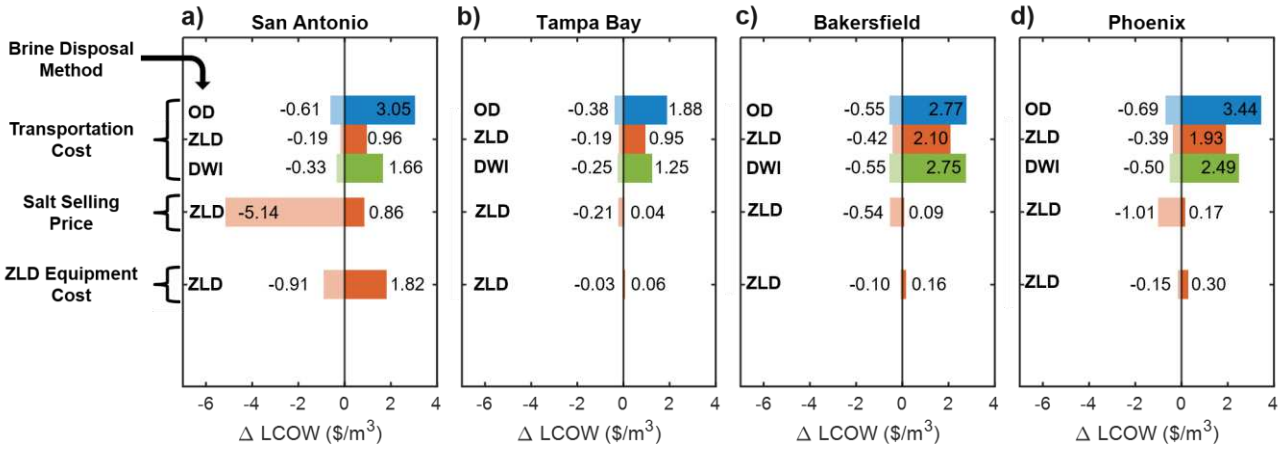


Fig. 8: Sensitivity analysis showing the change in levelized cost of water (ΔLCOW) resulting from variations in feed/brine transport cost, salt selling price, and ZLD equipment capex for the three brine management strategies associated with PW desalination: ocean discharge (OD), deep well injection (DWI), and zero liquid discharge (ZLD). The parameter ranges used in this analysis are detailed in the Methods section. Results are presented for four representative U.S. cities: **(a)** San Antonio, TX; **(b)** Tampa Bay, FL; **(c)** Bakersfield, CA; and **(d)** Phoenix, AZ. Positive values indicate an increase in LCOW, while negative values represent a reduction in LCOW relative to the baseline case shown in Fig. 7.

Framework for Feed Source Utilization and Brine Management

To provide a broader perspective on the implications of this geospatial technoeconomic analysis, Fig. 9 summarizes the relationship between feed salinity, distance from the coast, brine disposal strategy, and population distribution across the United States. The results shown in Fig. 9a for BGW and PW, indicate that OD is generally the preferred brine management strategy for locations within approximately 500 – 700 km of the coastline (horizontal distance only) due to the relatively low cost associated with direct brine disposal to the ocean. As distance from the coast increases, brine transport costs become increasingly important and alternative inland disposal approaches become more favourable. For inland regions with relatively low feed salinities (< 1 wt.%), DWI becomes the preferred brine management option because it avoids long-distance brine transport by disposing brine underground. For inland regions with higher feed salinities (> 1 wt.%), ZLD becomes increasingly viable because the quantity of recoverable salts can generate revenue that partially offsets the additional capital and operating costs associated with ZLD. More detail on the conclusions made from Fig. 9a can be found in Supplementary Note S8.

A second analysis was conducted to evaluate the population coverage associated with each cost-optimal brine management approach (see Methods). For BGW feed, OD was most cost-effective, accounting for approximately 59% of the population, followed by DWI (35%) and ZLD (6%), as shown in Fig. 9b. For PW feed, DWI was most cost-effective, accounting for approximately 62% of the population, followed by ZLD (31%) and OD (7%). Although DWI was the economically preferred option at fewer locations across the United States, the water produced by the desalination systems incorporating DWI served the largest fraction of the population, followed by ZLD.

The results in Fig. 9c show the population distribution associated with each feed source, with BGW representing the largest desalination resource accounting for 88% of the population. In comparison, PW resources account for approximately 11% of the population, while seawater resources accounts for only ~1%. This distribution reflects the widespread availability of BGW resources in inland regions, whereas seawater desalination is primarily restricted to coastal areas. It is important to note that this is only feasible if abundant BGW is available without causing adverse environmental impacts. Currently, most of the water supplied for human use is sourced from surface water bodies, such as lakes and reservoirs, or from fresh groundwater. Therefore, the results presented in Fig. 9c show the potential distribution of feed sources if all freshwater was generated from desalination. Additional information on the comparison of feed sources and brine management approaches can be found in Supplementary Note S8.

Overall, these results provide a nationwide framework for identifying economically favourable desalination and brine management pathways. The analysis demonstrates that the optimal brine disposal strategy is governed primarily by feed salinity and distance from the coast, while population distribution patterns highlight the potential of BGW and PW as alternative freshwater resources for inland regions. The SEC and LCOW estimates for BGW and PW herein are based on ideal-solution behavior; therefore, actual systems may exhibit higher energy consumption and water costs, particularly at elevated salinities.

These findings also provide additional context to compare desalination with AWH as freshwater production technologies. Geographically widespread BGW and PW resources can provide freshwater to approximately 99% of the U.S. population, including in inland regions, by combining desalination with cost-optimal brine management to achieve LCOW values of 0.29 – 5 $/m³. In contrast, our previous technoeconomic analysis showed that practical sorbent-based AWH systems, albeit the lowest cost among AWH technologies in arid environments, exhibit LCOW values ~ 11–13 $/m³[8]. As such, sorbent-based AWH is economically viable only in locations where saline water is unavailable and water transport costs from the coast are exceptionally high. This, along with its relatively low water yield, makes it suited for decentralized potable water production, whereas desalination systems can be scaled to supply municipal, industrial, agricultural, and commercial water demands across the United States. The technoeconomic framework presented here therefore extends previous comparisons between desalination and AWH by demonstrating that careful selection of the feed source and brine management approach further improves the competitiveness of desalination relative to decentralized atmospheric water harvesting.

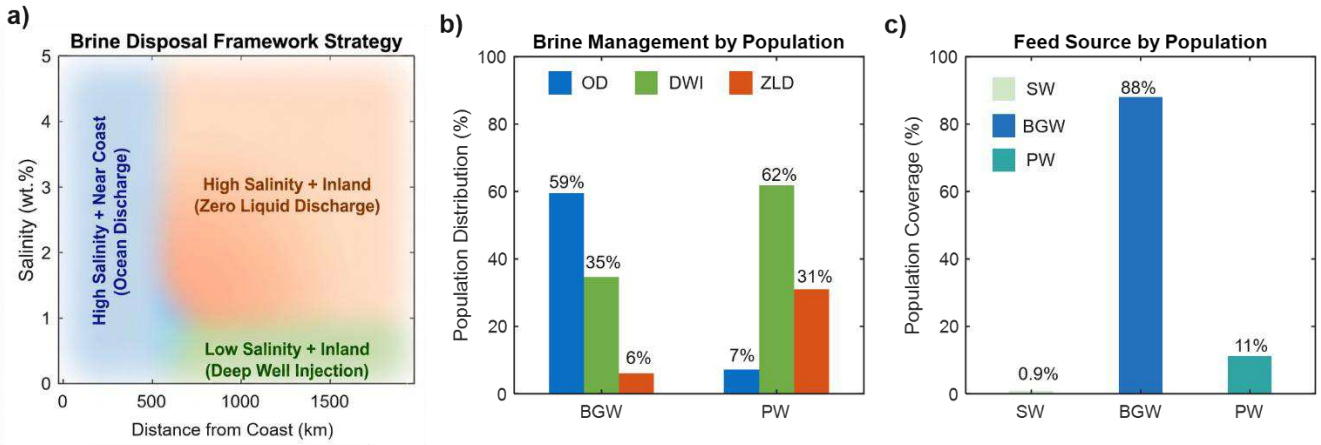


Fig. 9: (a) Conceptual framework illustrating the cost-optimal brine management strategy as a function of feed salinity and distance from the coast. **(b)** Population distribution associated with the optimal brine management strategy for brackish groundwater (BGW) and produced water (PW) feeds, showing the fraction of the U.S. population located where ocean discharge (OD), deep well injection (DWI), or zero liquid discharge (ZLD) is the preferred brine management option. **(c)** Population distribution associated with SW, BGW, and PW feed sources, showing the fraction of the U.S. population located in regions where each feed source is the most economically viable to desalinate.

Conclusion

This work presents a techno-economic framework for evaluating desalination of different feed sources and brine management strategies across the United States. Rather than focusing on a single desalination technology or disposal pathway, the framework integrates feed salinity, transport distance, brine management approach, and geographic location into a unified decision-making tool to identify freshwater production pathways that yield the lowest levelized cost of water (LCOW). Key findings from this analysis are:

- Ocean discharge (OD) is favorable for locations within approximately 500–700 km of the coastline, where transportation costs remain relatively low and LCOW values can be maintained ~ 1–2 $/m³. However, as distance from the coast increases, transportation costs rapidly become a dominant contributor to LCOW, reducing the practicality of seawater desalination for inland applications.
- For inland regions with low-salinity feeds (<1 wt.%) and increasing distance from the coast, deep well injection (DWI) becomes increasingly favorable because it avoids long-distance brine transport. In these regions, the low salt content provides limited opportunity for resource recovery, making disposal more economically favourable than brine concentration. LCOW values between 1–3 $/m³ can be achieved for many BGW and PW resources. Consequently, DWI is an effective transitional solution for expanding inland desalination capacity in geographic regions where it is permitted.
- For higher-salinity inland resources (>1 wt.%), zero liquid discharge (ZLD) becomes increasingly viable because greater quantities of recoverable salts help offset the additional costs associated with the brine concentration and crystallization components.

Ultimately, this analysis framework and case study enables researchers, utilities, and policymakers to evaluate desalination systems not only in terms of their treatment performance but also based on geographic suitability, saline

resource availability, and long-term economic feasibility, providing a pathway toward sustainable freshwater production.

Methods

Analysis Assumptions

For this analysis, only data points with feed salinities within the range of 0.05–4.8 wt.% were included. Salinities below 0.05 wt.% were excluded as they are treated as fresh enough that desalination is unnecessary for potable water[69-73]. Salinities exceeding 4.8 wt.% were excluded because RO is designed for seawater salinities around 3.5 wt.% or below[73-77]. For each feed, the LCOW was calculated at every latitude and longitude across the continental United States.

Seawater (SW) feed was assumed to originate from the nearest coastline corresponding to each latitude and longitude analysed. Brine transport costs associated with ocean disposal were assumed to be negligible due to the proximity of these facilities to the coast. For the BGW and PW feeds, the nearest available source was used for a selected site (latitude and longitude), with the associated feed transport to this site and brine transport to the ocean (OD) included in the LCOW analysis. An alternate approach is to evaluate all available BGW or PW sources, and then select the source that yields the lowest LCOW. Results using this alternate approach are provided in Supplementary Note S9. For OD, when determining the closest coastline to each location, only regions classified as coastal areas were included in the analysis. As a result, the Great Lakes were excluded from the coastal distance calculations. Additional details are provided in Supplementary Note S1.

For DWI, brine disposal in underground wells was assumed to be feasible, although in practice this will be determined by regional geologic and regulatory constraints. Since spatial data on injection wells was not available, this simplifying assumption was used to enable a comparison of brine management options. For the salt-recovery portion of the ZLD analysis, all feed sources were assumed to comprise predominantly of dissolved salt, with sodium and chloride as the primary constituents. In practice, these feeds especially PW are chemically complex and may contain organics, metals, and other non-salt constituents [78-81].

For this analysis, a baseline salt selling price of 30 $/ton was used based on a compilation of values reported in the literature for various recovered salts. The reported prices include those for NaCl, mixed salts, $CaCl_2$, $CaCO_3$, and other commercially relevant salts[30,62,82-91]. A detailed summary of the reported salt prices used to establish the baseline value is provided in Table S2 in Supplementary Note S2.

Sensitivity Analysis

To assess the impact of the three brine management approaches evaluated in this study, a sensitivity analysis was conducted to determine how the levelized cost of water (LCOW) varied with transport cost, ZLD equipment cost, and salt selling price above and below their baseline values (see Table S1 in Supplementary Note S2). These parameters were selected because of their significant variability within the literature and the limited availability of data beyond lab-scale and pilot demonstrations. Transport cost was varied by a factor of five to reflect the uncertainty and regional variability reported in prior studies. The salt selling price was varied by a factor of six to evaluate the extent to which ZLD depends on revenue generated through salt recovery. Finally, ZLD equipment costs (MVC and EP) were varied by a factor of two to capture the range of values reported in the literature for commercial systems.

Population Distribution

To extend the geospatial technoeconomic results, an additional analysis was conducted to evaluate feed source selection and brine management strategy on a population-weighted basis. At each evaluated latitude and longitude, the brine management configuration associated with the lowest LCOW was identified (OD, DWI, or ZLD). For the brine analysis, the population associated with each location was grouped according to the optimal brine management strategy (and summed across all evaluated locations). For the feed source analysis, populations were grouped according to whether the lowest-cost configuration utilized SW, BGW, or PW. The spatial optimization results were subsequently used to develop the generalized brine management framework shown in Fig. 9, which summarizes the relationship between feedwater salinity, distance from the coast, and the cost-optimal feed source and brine management strategy.

Author Contributions

Conceptualization, A.K.M. and J.D.K; methodology, W.P.P. and J.D.K; investigation, W.P.P.; writing W.P.P. and A.K.M.; funding acquisition, A.K.M.; supervision, A.K.M.

Conflicts of Interest

There are no conflicts to declare.

Data Availability

Source data is provided with the paper. All other data supporting the findings of this study are available from the corresponding author upon reasonable request.

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