THESIS

MULTI-OBJECTIVE OPTIMIZATION OF THE ECONOMIC FEASIBILITY FOR MOBILE ON-SITE OIL AND GAS PRODUCED WATER TREATMENT AND REUSE

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ABSTRACT

MULTI-OBJECTIVE OPTIMIZATION OF THE ECONOMIC FEASIBILITY FOR MOBILE ON-SITE OIL AND GAS PRODUCED WATER TREATMENT AND REUSE

Development of unconventional oil and gas wells has resulted in large volumes of produced and flowback water that require careful handling to minimize environmental and human health risks due to high concentrations of salt and other contaminants. Common practice is to truck the wastewater from well sites to Environmental Protection Agency (EPA) Class II underground injection control (UIC) wells. The cost of transportation often accounts for much of the handling costs. As an alternative, on-site desalination followed by surface water discharge of the water product for downstream reuse has the potential to lower handling cost by reducing the volume of water requiring transport to UIC wells while additionally alleviating strain on water supplies in arid regions. In contrast to centralized FP water treatment, capacity factor for on-site desalination is highly dependent on management strategy and shale bed characteristics. Therefore, this work studies how accounting for capacity factor might determine the attributes of an optimal management strategy and the cost of produced water treatment. The volume of wastewater to be treated by desalination, the method for desalination unit deployment, desalination unit capacity, and desalination technology (membrane distillation, mechanical vapor compression, and reverse osmosis) are decision variables defining a management strategy. This work explores different produced and flowback water management strategies in Weld County, Colorado, to determine a set of Pareto optimal produced water management strategies from a techno-economic and environmental perspective optimizing economics and water reclamation. Results show that as the desired level of water reclamation increases there is an increase in the marginal cost of water reclamation. Ultimately, the optimal volume of wastewater to be reused was determined to be between 50% and 88% of the total produced costing between \$5.82 and \$9.79 per m^3, respectively, in Weld County, CO where business as usual operation (injection) cost is \$7.68 per m^3. Generally, optimal management strategies, when accounting for capacity factors, utilized packaged desalination units of 100 m^3/d capacity with deployment location reevaluated on a 1-6 month planning horizon.

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1. INTRODUCTION

Development of unconventional oil and gas wells has led to a flood of high salinity wastewater posing environmental and human health risks if introduced directly to the environment. Approximately, 3.4 billion m^3 (21.4 billion bbls) of wastewater are produced annually by the oil and gas industry in the United States (Scanlon et al., 2020). This wastewater, in the form of flowback water and produced water (FP water), can have salinities ranging from a couple hundred ppm to 400,000 ppm total dissolved solids (TDS) the latter of which is an order of magnitude higher than seawater (Chang et al., 2019, Scanlon et al., 2020, Fakhru'l-Razi et al., 2009, Mohammad-Pajooh et al., 2018). Flowback and produced waters are mixtures of fluid injected for hydraulic fracturing and water that was originally present in the shale formation. Flowback water has a high flowrate, up to 1000 m^3/d, but only lasts for a short period after well completion, termed the flowback period (Chang et al., 2019). Produced water refers to the water generated from a shale well over the course of its life, after the flowback period. The flowrate of produced water is typically steady at 2-8 m^3/d (Chang et al., 2019). For the purpose of this paper, no distinction is made between flowback water and produced water, as both must be properly managed.

FP water must either be treated or injected deep underground to minimize surface and/or ground water contamination because of its high salinity and the presents of contaminants such as naturally occurring radioactive material, petroleum, boron, other organic compounds and hydraulic fracturing chemicals (Scanlon et al., 2020). Common practice is to either reuse the FP water for enhanced oil recovery (EOR) or dispose of it in an Environmental Protection Agency (EPA) Class II underground injection control (UIC) well, commonly referred to as injection

(Veil, 2015). One of the biggest problems with injection is induced seismic activity (McGarr et al., 2015, Ellsworth, 2013, Brown et al., 2017, Horton, 2012). While reuse of FP water for EOR is an effective way to reduce the fresh water demand of unconventional oil and gas, it is not a sustainable option for disposal of all FP water; the volume of FP water requiring disposal often outweighs the demands of EOR or hydraulic fracturing fluid (Scanlon et al., 2020, Chang et al., 2019).

In light of these challenges, other alternative approaches to injection have gained traction in recent years (Robbins et al., 2020a, Robbins et al., 2020b, Tavakkoli et al., 2017, Tavakkoli et al., 2020, Mohammad-Pajooh et al., 2018, Wenzlick and Siefert, 2020, Dolan et al., 2018, Vengosh et al., 2014, Tong et al., 2019, Chang et al., 2019). On-site desalination is an alternative that has the potential to decrease the volume of water requiring transportation to UIC wells. Furthermore, beneficial reuse of FP waters as an alternative to injection, especially in arid regions, could help increase water security (Meng et al., 2016). Half of the developed basins in the United States exist in regions of high water scarcity, such as Colorado, California, and Texas (Vengosh et al., 2014). The advantage of on-site desalination is a decrease in wastewater transport (either to UIC wells or to centralized treatment plants) by up to 85%, depending on the recovery factor of the technology (Tavakkoli et al., 2020, Robbins et al., 2020b, Mohammad-Pajooh et al., 2018). This reduces transportation cost, a major component of total handling cost, but there are difficulties to deploying and managing a network of on-site desalination units. Previously, the cost of small scale desalination had been prohibitively expensive, but studies have shown that the cost of desalination is now low enough to compete with disposal, depending on well-site-specific transportation distances (Tavakkoli et al., 2017, Tavakkoli et al., 2020, Wenzlick and Siefert, 2020, Osipi et al., 2018, Schwantes et al., 2018). All the aforementioned desalination techno-economic studies (Tavakkoli et al., 2017, Tavakkoli et al., 2020, Wenzlick and Siefert, 2020, Osipi et al., 2018), have assumed capacity factors of 90%. This assumption accounts for maintenance downtime and is common for centralized plant analysis (Al-Obaidani et al., 2008), but breaks down for on-site treatment. Unsteady and variable FP water flowrates (Bai et al., 2015) make the determination of an appropriate capacity factor for on-site desalination non-trivial but previous studies have neglected this and oversimplified their estimates of equipment cost. Additionally, when a site has short transportation distances and low transportation costs, total management cost becomes dominated by desalination cost which can be greatly underestimated by misrepresenting capacity factor.

Flexible capacity scaling is important when the demand for treatment varies significantly (Mohammad-Pajooh et al., 2018) because without it, a high capacity factor can be difficult to achieve. Demand for produced water treatment at a single well declines drastically after the first few months of its operation; 10-20% of total FP water produced over a well's lifetime surfaces in the first 3 months of operation and 20-50% in the first 6 months of operation (Kondash et al., 2017). Using curve fits from Bai et al., 2015 (flowrates decayed from 1,300 to 13 barrels per day), it was estimated that approximately 13,000 barrels of produced water storage would be required if all the FP water produced at a typical well in the Denver-Julesburg (DJ) Basin over its first year of operation was to be desalinated at the average FP water flow rate during that year (65 barrels per day). It is apparent that an on-site desalination unit cannot remain stationary at a single well for its entire useful life without a prohibitively large storage capacity or a declining capacity factor throughout its useful life but studies to date have neglected relocation cost and assumed constant capacity factors. This study, in order to account for highly fluctuating FP water production and management demand, models the redistribution of on-site treatment units to wells that have the highest flowrates. In this manner, the model accounts for how a company operating within an oil basin could deploy a fleet of standard sized packaged mobile on-site treatment units to meet FP water demand across all their well sites.

This paper analyzes the logistics for on-site desalination of FP water and determines an optimal management and deployment strategy in Weld County, Colorado while accounting for packaged plant capacities, variable capacity factors, and deployment costs. Weld County was selected because a well in Weld County can experience an 84% reduction in FP water volume during its first 30 days of operation (Bai et al., 2015), and unlike the Marcellus shale, there is no scarcity of UIC wells in Weld County which reduces transportation distances and increases the importance of maintaining a high capacity factor. The number of mobile packaged desalination units to be purchased, the method for desalination unit deployment, the desalination technology, and desalination unit capacity are decision variables defining a management strategy. Membrane distillation (MD), reverse osmosis (RO), and mechanical vapor compression (MVC) are considered to represent a set of desalination technologies with a range of potential desalination costs and differing potentials for water recovery. This work explores different FP water management strategies to determine a set of Pareto optimal FP water management strategies with a focus on striking a balance between minimizing economic barriers and maximizing water recovery.

The novelty of this work is in accounting for previously neglected costs associated specifically with on-site desalination, by incorporating the concepts of packaged plant capacities, variable capacity factors, and deployment costs into the model. The standardized capacity of a mass produced packaged plant is considered for the first time and the previously neglected cost of FP water management demand dropping below the standardized capacity, leading to low capacity factors, is accounted for. As another first, the model quantifies the cost of redeploying and setting up a desalination unit at new well sights as demand fluctuates. Discussion focuses on the influence these novel parameters have on economies of scale, the frequency of desalination unit redistribution, and the level of reuse on capacity factor and total management cost as opposed to focusing on a detailed techno-economic assessment of MD, RO, or MVC. An open-source decision support tool that can be used to evaluate case specific desalination costs and adapted to other basins is published as a part of the work.

2. METHODS

FP water production data, transportation routes, and the spatial locations of wells were collected for Weld County, Colorado (Section 2.1 and Section 2.2). The data was subsequently used, to determine capacity factors of desalination units deployed at individual wells and their site-specific brine disposal costs, together with economic inputs (Section 2.3) in a techno-economic model to determine site-specific management cost (Section 2.4). First, the influence of capacity factor and transportation distance on total management cost for a single candidate treatment location was investigated using the techno-economic model. Then, to find near optimal solutions, the model was iteratively run with varied combinations of decision variables as inputs to populate a subset of all possible FP water management solutions. The solutions were plotted in objective space (on cost vs reuse axes) so that the tradeoffs such as those between capacity factor and economies of scale and between capacity factor and the frequency of unit redistribution could be quantified (Section 2.5). Ultimately the Pareto frontier was defined using the epsilon constraint method with varied values of epsilon.

2.1 Transport Route Data

Accurate representation of transportation costs is important to the economic model; the largest benefit of on-site treatment comes from reduced transportation cost (Figure 1). Transportation cost from a well to an on-site desalination unit is considered negligible as the systems are assumed to be co-located. Additionally, water product from desalination does not require transportation to a disposal well because it was assumed to meet surface discharge requirements. It was assumed that the product water could be pumped using lay-flat HDPE pipe because the median distance to the nearest body of water suitable for surface discharge for 20 randomly selected wells was 0.61 miles. Therefore, transport cost of the product water from the well to a surface discharge site was also considered negligible when compared to the trucking cost required for injection. Fakhru'l-Razi et al., 2009, estimates the cost of different disposal methods to be 0.01 - 0.08 $/bbl for surface discharge, 0.05 - 2.65 $/bbl for disposal wells, and 0.01 - 5.50 $/bbl for commercial water hauling. Where desalination is implemented, only the brine requires transport to an UIC well (Figure 1).

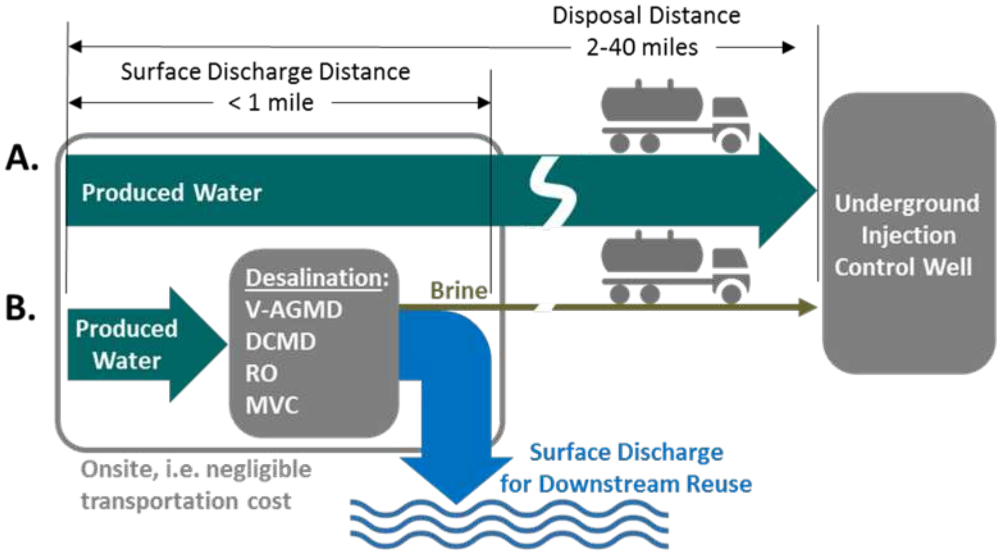

Figure 1: A) Produced water is trucked from the wellsite to a disposal well (business as usual). B) Onsite desalination is followed by surface discharge of the distillate. Only the brine requires transport to a disposal well.

To determine the transportation distance from a production well to its nearest disposal well, procedures outlined in our previous study (Robbins et al., 2020a) were utilized. Using ArcGIS 10.6 software, the nearest disposal well was identified for each production well. The Network Analyst toolbox of ArcGIS 10.6 along with a TIGER/Line shapefile that depicts the road infrastructure in Weld County were used to accurately calculate the route distance from producing well to nearest disposal well (ESRI, 2018; U.S. Census Bureau, 2019).

In Weld County, trucking is the most used method to transport UOG wastewater to a disposal well. A typical UOG wastewater truck used in Weld County has a capacity of 120 barrels (19 m^3) (Neal, 2019). The truck capacity with the route distance and wastewater volume (brine or FP waters) for each well was integrated to calculate the total one-way transportation distance to move all wastewater generated from each UOG production well to the nearest disposal well. The distance to the nearest UIC well ranges from 2-40 miles.

2.2 Unconventional Oil and Gas Wastewater Data

FP wastewater data was collected with a monthly resolution for wells hydraulically fractured between January 2015 and April 2020 in Weld County. Within this time period, 5,019 wells were hydraulically fractured and began production. Monthly FP water production data for these wells was obtained from the Colorado Oil and Gas Information System (COGIS) database managed by the Colorado Oil and Gas Conservation Commission (COGCC) (COGCC, 2020). FP water flows at the prior locations during a one year period from May 2019 through April 2020 were collected. The locations of these wells were also obtained using the COGIS database. Additionally, the number (47) and locations of active disposal wells in Weld County were also obtained via the COGIS database using the facility inquiry function.

Water quality data was not available for specific wells. Rather the water salinity was assumed to be 30,000 ppm TDS for all wells. The salinity of the DJ basin ranges from 14,220 to 44,502 ppm TDS (Chang et al., 2019, Scanlon et al., 2020, Dolan et al., 2018, Tong et al., 2019). This influent TDS concentration directly impacts the recovery factor of a desalination technology (Section 2.3).

Figure 2 depicts the data collected for the case of Weld County. The flowrate of FP water varies dramatically over time (Robbins et al., 2020b, Bai et al., 2015). Both the monthly variance and magnitude of the FP water flowrate at any candidate location is a function of the age of the well. Two extremes are presented in Figures 2a and 2b. From the coordinates acquired above, individual wells were grouped into clusters of wells where there is potential to treat FP water collectively. Grouping wells also increases the magnitude of FP water flowrate at candidate locations allowing for better economies of scale.

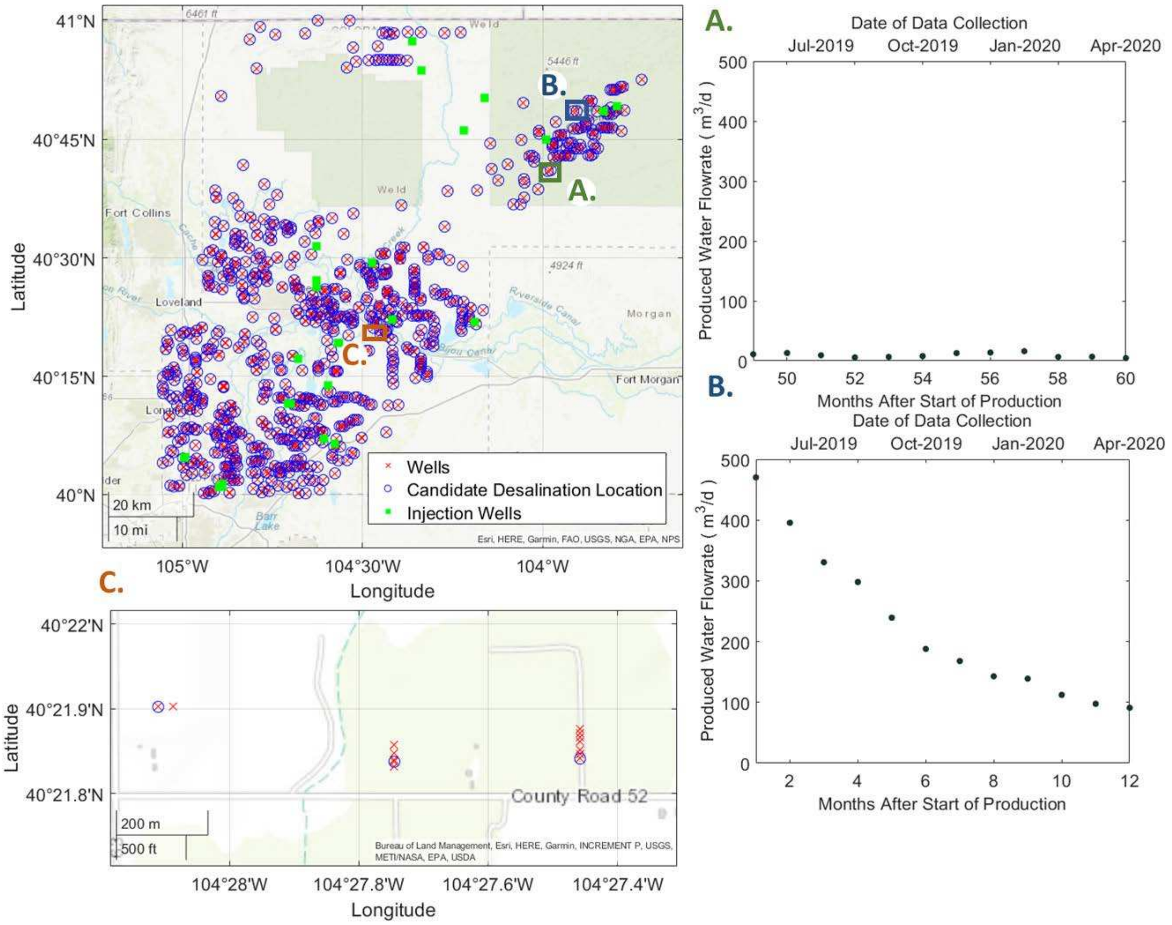

Figure 2: Produced water data was collected for all the wells represented by a red 'x' in Weld County, Colorado over a one year period. (May 2019 through April 2020). Blue circles indicated the candidate desalination locations considered. A) Produced water flow from a 4 year old well. B) Produced water flow from a new well. C) Close up look at 3 well pads collectively treating FP water from multiple wells within a quarter mile radius at a single candidate desalination location.

One portable desalination unit is capable of treating water from multiple wells, especially when multiple horizontal wells are drilled from the same well pad. It is not uncommon for 20 or more wells to be located at the same well pad (Abramov, 2019). In this study, it was assumed that the FP water from all the wells at a single well pad, or more generally, all the wells within a quarter mile radius would be treated collectively at one candidate desalination location (Figure 2c). For the 5,019 wells shown in Figure 2, there are 755 candidate treatment locations.

2.3 Desalination Technologies

In addition to transport of water, the costs associated with relocating desalination unit are determined. These costs have been termed relocation costs. They are dominated by installation labor because shipping distances between producing wells are extremely short. It was assumed that the desalination technologies could fit into 1-2 standard shipping containers (BeJemaa, 2009), or at worst 10 containers based on a footprint of 0.34- 0.77 m^2 per m^3 capacity as suggested by Mohammad-Pajooh et al., 2018. It was assumed 80-560 man hours at $23 per hour were required for installation. This was based on an estimated installation time of 1-7 days for portable desalination units (Queensland Government and Mohammad-Pajooh et al., 2018) and a work crew of 2 men. Based on labor, $3000 was chosen to represent the middle ground and $10,000 for the high end of relocation costs. The other costs associated with desalination: equipment, energy, chemical, pretreatment, maintenance, and labor costs, were derived from a literature review of RO, MVC, and MD. All capital costs reported from literature have been converted to 2018 dollars using the chemical engineering plant cost index (Appendix A). A key difference between an on-site and centralized management approach that has not been previously addressed is that an on-site desalination plant cannot be custom built for a predicted design flowrate in the same way as a centralized plant. Considering the extremely variable nature of FP water, it is not reasonable to build thousands of custom built small scale treatment units. Therefore, in this paper, packaged units of 10, 100, and 1000 m^3/d treatment capacity are considered. The following sections detail the assumptions made in regard to the different water treatment technologies. Historically, the goal of many studies in the field of desalination has been to determine the viability of desalinating brackish water or seawater to produce potable water. Consequently, the functional unit used in these studies is a cubic meter of permeate (clean potable water). The recovery factor is used to convert costs from literature reporting values in \$ per m^3 permeate to the values in \$ per m^3 feed used in this study. Pretreatment infrastructure was approximated to cost \$153 per m^3/d capacity (Sirkar and Song, 2009, Tavakkoli et al., 2017). Desalination equipment constitutes the majority of capital expenditures (CAPEX). For MD and RO, desalination equipment can be broken down into membrane module cost and rest of plant cost. Energy, labor, maintenance, chemicals, and membrane replacement constitute the modeled operating expenditures (OPEX) for desalination technologies.

2.3.1 Reverse Osmosis

RO is an energy efficient membrane technology compared to other desalination technologies, requiring 2-6 kWh/m^3 feed water (Bhojwani et al., 2019, Schwantes et al., 2018, Plumlee et al., 2014, Sirkar and Song, 2009, Fiorenza et al., 2003, Chang et al., 2019, Kesieme et al., 2013). However, RO is ineffective for highly saline water because it can only concentrate feed water up to 70,000 ppm TDS (Schwantes et al., 2018, Chang et al., 2019). In Weld County, where FP water salinity is around 30,000 ppm TDS, a maximum recovery factor of only 57% can be expected. RO operates on electricity, requiring a connection to the grid or a generator on site. CAPEX in Table 1 reflect the results of a vendor survey conducted by the Queensland Government for portable sea water RO units in the range of 100 m^3/d to 5000 m^3/d. These costs are corroborated by Fiorenza et al., 2003, Sirkar and Song, 2009, Bhojwani et al., 2019, Kesieme et al., 2013, and Wenzlick and Siefert, 2020, and total treatment costs align with those reported by Pinto and Marques, 2017. Maintenance was assumed to be 2.5% of CAPEX (Kesieme et al., 2013, Schwantes et al., 2018, Bhojwani et al., 2019).

2.3.2 Mechanical Vapor Compression

Another well-established commercially available desalination technology is MVC. MVC is capable of concentrating brines up to 250,000 ppm TDS (Tong et al., 2019); a recovery factor of 88% is assumed for the produced water from Weld County. MVC is still relatively efficient compared to MD, with an electrical energy demand of 7-55.4 kWh/m^3 feed depending in influent TDS (Bhojwani et al., 2019, Schwantes et al., 2018, Tong et al., 2019, Fiorenza et al., 2003). However, equipment is expensive because of moving parts and a need to be corrosion resistant. Equipment costs were approximated to match vendor reported data from the work of Schwantes et al., 2018. Maintenance was assumed to be 1% of CAPEX (Schwantes et al., 2018, Bhojwani et al., 2019).

2.3.3 Membrane Distillation

A relatively new and evolving thermal desalination technology is MD. Therefore, there is uncertainty in both current and prospective desalination costs. Several techno-economic studies were used to develop a range of prospective MD costs. MD can be classified into numerous subcategories, such as direct contact membrane distillation (DCMD), and vacuum air gap membrane distillation (v-AGMD). There are tradeoffs between CAPEX and operating expenses (OPEX) for each technology (Schwantes et al., 2018). Winters et al., 2017, recently defined a correlation between membrane flux and energy consumption representing a tradeoff between CAPEX and OPEX in DCMD modules. An attempt to optimize the MD process is beyond the scope of this study. Instead, two specific techno-economic studies of unique designs, DCMD represented through the work of Tavakkoli et al., 2017 and v-AGMD represented through the work of Schwantes et al., 2018 were chosen to represent two prospective MD technologies.

There are some inherent similarities within MD regardless of specific design. In this study, MD was assumed capable of concentrating brines up to 250,000 ppm TDS (Schwantes et al., 2018) but values as high as 350,000 ppm have been reported (Chang et al., 2019, Tavakkoli et al., 2017). A recovery factor of 88% is assumed for produced water from Weld County. MD is very energy intensive with reported specific energy consumption much higher than MVC or RO, but can readily use waste heat or burn natural gas on-site for thermal energy (Chang et al., 2019, Kesieme et al., 2013, Al-Obaidani et al., 2008, Tavakkoli et al., 2017, Lokare et al., 2017, Robbins et al., 2020b). Exact energy consumption varies between designs. In this model the energy consumption of MD was defined by a gained output ratio (GOR), or the ratio of the energy entering the system to the energy required for distillation (Schwantes et al., 2018). GOR can be greater than 1 because of internal energy recovery. A GOR of 1 signifies that the energy entering the system is equivalent to the energy required for direct evaporation without heat recovery (Schwantes et al., 2018). Specific membrane cost and specific membrane module cost were assumed to be the same regardless of design or module type (Schwantes et al., 2018). Based on vendor inputs, perspective specific module costs (including hot side heat exchanger) range from \$59 - 183 per m^2 depending on economies of scale (Schwantes et al., 2018). Membrane cost was assumed to be 10% of module costs (Schwantes et al., 2018). While specific module cost (cost per membrane area) are independent of design, total module costs are dependent on the membrane area. Membrane area differs between the two studies because of differences in design. Therefore, the module cost was determined from membrane flux which is design specific. Rest-of-plant costs, including heat exchangers, piping, pumps, instrumentation and controls, were also assumed to be design specific because of differences in energy recovery and design. Therefore, heat exchanger costs were removed from module cost and were added back into the model separately. Chemicals for pretreatment and membrane cleaning were approximated as \$0.02 per m^3 (Al-Obaidani et al., 2008, Sirkar and Song, 2009, Helal et al., 2003). Membrane lifetime was assumed to be 5 years (Tavakkoli et al., 2017). Maintenance was assumed to be 2.5% percent of CAPEX (Schwantes et al., 2018).

DCMD does not perform well with large membrane areas because of high heat transfer between the permeate and brine streams. Therefore, it trends toward higher transmembrane fluxes but lower energy recovery and GOR (Schwantes et al., 2018, Lokare et al., 2017). The GOR for DCMD was assumed to be 1.2 (Tavakkoli et al., 2017, Lokare et al., 2017). The designs proposed by Lokare et al., 2017 and Tavakkoli et al., 2017 utilize a membrane area of 2.4 - 3.6 m^2 per channel. Flux has been reported between 3.5 - 26.5 kg m^{-2} hr^{-1} for a DCMD membrane of this area (Lokare et al., 2017, Schwantes et al., 2018, Sirkar and Song, 2009). For this study a membrane area of 2.4 m^2 per channel and a more conservative flux of 8 kg m^{-2} hr^{-1} were assumed to represent DCMD. The design of Tavakkoli et al., 2017, relies heavily on heat exchangers for energy recovery. Because of this, they contribute significantly more to rest-of-plant CAPEX than the design proposed by Schwantes et al., 2018. Heat exchanger cost was scaled using a reference capacity and a degression coefficient of 0.8 (Schwantes et al., 2018) (Appendix A). The remaining rest-of-plant costs (excluding heat exchangers) for DCMD were approximated as the system costs of an air gap membrane distillation (AGMD) unit of an equivalent capacity: \$2500-\$6700 per 50 m^2 module depending on treatment capacity (Schwantes et al., 2018). Like DCMD, AGMD is simpler than v-AGMD and excludes extra piping and vacuum pumps.

v-AGMD can maintain a viable temperature difference over larger areas because it has better insulation between distillate and brine streams (Schwantes et al., 2018). Larger areas lend towards better energy recovery and lower fluxes (Schwantes et al., 2018). For this study, a membrane area of 9.8 m^2 per channel corresponding to a transmembrane flux of 1.3 kg m^{-2} hr^{-1} was selected (Schwantes et al., 2018). GOR for v-AGMD was assumed to be 3.7 (Schwantes et al., 2018). v-AGMD is more efficient and complex, including a vacuum pump, and therefore has higher assumed rest-of-plant CAPEX (excluding heat exchangers): \$3200-\$8000 per 50 m^2 module depending on treatment capacity (Schwantes et al., 2018). Heat exchangers do not account for as large a portion of rest-of-plant cost in this design; only a brine stream heat exchanger was considered.

2.4 Techno-Economic Analysis

The system boundary for this study was limited to the handling of oil and gas wastewaters; the revenues from natural gas and the water footprint of hydraulic fracturing were neglected. FP water storage was considered outside the system boundary. It was assumed that both business as usual (BAU) management and desalination will require similar volumes of storage to hold water awaiting injection or desalination. The functional unit used is one cubic meter of FP water managed because the goal of this paper is to dispose of FP water. When desalination is the management method, it is one cubic meter of FP water treated by desalination, or one cubic meter of feed water.

CAPEX, such as trucks and injection well equipment, are assumed to be outsources to trucking companies and third-party disposal wells. These costs were assumed to be incorporated into the cost of transportation and injection, respectively. The cost of third-party injection in Colorado is \$4.09 per m^3 (Colorado State Land Board). The cost of transportation by truck is

$105 per hour (Robbins et al., 2020a). It was assumed that steam would be generated as a source of thermal energy. The cost of steam was assumed to be $3.36 per 1000 pounds (Kumana & Associates, 2003). The cost of electricity is assumed to be $0.07 per kWh based on the rate for an industrial user in Colorado (U.S. Energy Information Administration, 2021). The opportunity cost associated with burning natural gas for steam generation and the cost of equipment for electricity generation is assumed to be included in these prices.

Desalination CAPEX are amortized using a fixed charge rate and a capacity factor. As defined by National Renewable Energy Research Laboratory (NREL), a fixed charge rate is the amount of revenue that must be collected annually, per dollar of an investment, to pay the carrying charges on the investment. Fixed charge rate is a function of tax rate, inflation, internal rate of return, depreciation schedule, and expected lifetime. A fixed charge rate of 11.92% was assumed for this work to reflect an internal rate of return of 10%, a tax rate of 5% (Silbaugh, 2020), an MACRS 7 year depreciation schedule, and a lifetime of 20 years.

The capacity factor is the ratio of actual annual output (i.e., volume of treated FP water) to output at the rated capacity (i.e., FP water treatment capacity of the technology) for an entire year (NREL, 2020). The unit cost of desalination is a function of the capacity factor. Desalination costs reported in literature can compete with injection (Table 1). In Table 1, a fixed capacity factor of 90% was assumed, reflecting downtime (e.g., from maintenance, transportation, or lack of need) to compare the treatment costs assumed for this paper to those in literature. However, this is the upper limit of what can be expected; it may not be physically or economically feasible to attain this capacity factor due to the variable nature of FP water flows. The optimization model accounts for variable capacity factors.

Table 1: Total produced water management costs. These cost were approximated by assuming a capacity factor of 90% and a transportation

	Treatment Technology	Cost as a Function of Capacity 10 m^3/d	100 m^3/d	1000 m^3/d
Desalination OPEX ($/$m^3$)	**RO[a,c,e,f,g,h,j,m,p,q]**	$ 2.47	$ 0.92	$ 0.48
	MVC[a,b,f,j,m]	$ 6.58	$ 2.80	$ 1.78
	v-AGMD[b,e,g,h,l]	$ 6.83	$ 4.35	$ 3.61
	DCMD[d,e,g,h,l,n]	$ 9.80	$ 7.50	$ 6.86
	BAU	$ -	$ -	$ -
Desalination Specific CAPEX* ($/$m^3$)	**RO[k]**	$ 1.10	$ 0.72	$ 0.40
	MVC[b]	$ 21.54	$ 7.54	$ 3.42
	v-AGMD[b]	$ 3.97	$ 2.44	$ 1.47
	DCMD[b,d]	$ 1.80	$ 1.17	$ 0.75
	BAU	$ -	$ -	$ -
Transportation Cost ($/$m^3$)**	**RO**	$ 1.75	$ 1.75	$ 1.75
	MVC	$ 0.61	$ 0.61	$ 0.61
	v-AGMD	$ 0.61	$ 0.61	$ 0.61
	DCMD	$ 0.61	$ 0.61	$ 0.61
	BAU	$ 4.09	$ 4.09	$ 4.09
Disposal Cost ($/$m^3$)	**RO**	$ 1.47	$ 1.47	$ 1.47
	MVC	$ 0.52	$ 0.52	$ 0.52
	v-AGMD	$ 0.52	$ 0.52	$ 0.52
	DCMD	$ 0.52	$ 0.52	$ 0.52
	BAU	$ 3.44	$ 3.44	$ 3.44
Annualized Cost* ($/$m^3$)	**RO**	$ 6.77	$ 4.84	$ 4.09
	MVC	$ 29.03	$ 11.38	$ 6.28
	v-AGMD	$ 11.46	$ 7.63	$ 6.04
	DCMD	$ 12.64	$ 9.74	$ 8.70
	BAU	$ 7.53	$ 7.53	$ 7.53

* Capital cost annualized assuming a 20 year lifetime, 10% internal rate of return, and 90% capacity factor

** Assuming a 5.6 mile transportation distance

[a]Bhojwani et al., 2019, [b]Schwantes et al., 2018, [c]Plumlee et al., 2014, [d]Tavakkoli et al., 2017, [e]Sirkar et al., 2009, [f]Fiorenza et al., 2003, [g]Chang et al., 2019, [h]Kesieme et al., 2013, [j]Tong et al., 2019, [k]Queensland Government, [l]Al-Obaidani et al., 2008, [m]Osipi, 2018, [n]Lokare et al., 2017, [p]Wenzlick and Siefert, 2020, [q]Wittholz et al.,2008

Although there is no desalination cost associated with injection, the BAU scenario, on-site desalination can be cheaper than injection because of decreased injection and transportation costs. Assuming a transportation distance of 5.6 miles, the mean transportation distance for the wells considered in this study, the cost of transportation without desalination is \$4.09 per m^3 (Table 1). On-site desalination reduces transportation and injection cost by up to 88% (dependent on the recovery factor of the desalination technology). Labor cost accounts for the economies of scale in desalination OPEX (Table 1). There is great uncertainty in the magnitude of the economies of scale that might be experienced (see Limitations and Future Work). Economies of scale are also seen in CAPEX (Section 2.3).

2.5 Optimization

The collected data and the economic model come together to define a multi-objective optimization problem. A time period of one year, from July 2019 to June 2020, was analyzed. Data is available for the FP water production at each candidate treatment location with a monthly resolution. Decision space is an n-dimensional space where ‘n’ corresponds to the number of decision variables. Objective space is an m-dimensional space where ‘m’ corresponds to the number of objectives. In conjunction with the data, the model takes ‘n’ inputs, the decision variables, and maps them from decision space to objective space. The Pareto frontier exists in objective space and is composed of the set of points corresponding to “equally good” solutions. Equally good is defined such that no one objective can be improved without adversely affecting another. The Pareto frontier must always have a positive slope because the objective plotted on the y-axis (cost) is to be minimized while the objective plotted on the x-axis (reuse) is to be maximized.

2.5.1 Defining a Management Strategy

There are 4 decision variables that define a management strategy: Planning Horizon, Desalination Technology, Total Treatment Capacity (i.e. number of desalination units deployed), and Unit Treatment Capacity. The optimal management strategy defines the total number of desalination units deployed and the location of all desalination units during every planning horizon of the one-year study. First, the one-year study is divided into planning periods according to the decision variable Planning Horizon. Here, the planning horizon defines how far into the future an operator might account for when determining deployment locations and the length of deployment. For a planning horizon of 1 month there are 12 planning periods. For a planning horizon of 12 months there is only one planning period. The location of desalination units was re-ordered for each planning period by placing units in order of most profitable candidate location according to Equation 1,

$$Profit = ICS + TCS - OPEX - \frac{FCR * CAPEX}{AvgCF * Capacity * 365} \tag{1}$$

where, *ICS* and *TCS* are the savings, in \$/m^3, resulting from injecting and transporting a reduced volume of brine. This was repeated for each planning period in the one-year study. The profitability of a location is a function of the distance to the nearest UIC well and the cost of desalination in that location (Equation 1). When considering the deployment of additional treatment capacity to a specific location, the cost of desalination varies depending on the amount of water requiring treatment in that location (Equation 1). The operational cost of desalination, *OPEX*, is constant and is only a function of Desalination Technology and Unit Treatment Capacity (Table 1). However, the amortized desalination specific CAPEX (\$/m^3) for a desalination unit deployed to a particular location is a function of fixed charge rate (*FCR*), the equipment cost of a desalination unit (*CAPEX*), and the amount of water that can be treated in the particular location during the prescribed planning period. The product of capacity and average capacity factor (*AvgCF)* is the volume of water treated over the same time period which *AvgCF* was computed. The average capacity factor is defined by the volume of FP water treated by a unit deployed at a candidate location divided by the desalination capacity of the unit.

2.5.2 Objective Functions

The management strategy fixes the parameters, *OPEX, CAPEX, M, DP, RF*, and *U*, used in equations 2 to 7 to determine the value of the objective functions. The values of these variables are determined from a knowledge of the locations of all desalination units at all times which is provided by a management strategy defined according to Section 2.5.1. Desalination operational costs (*OPEX*), capital costs (*CAPEX*), and recovery factor (*RF*) are constrained by the combination of decision variables Desalination Technology and Unit Treatment Capacity (e.g., Table 1). Desalination Percent (*DP*) represents the percent of total FP water ($FP_{i,t}$) at candidate location 'i' during month 't' that is desalinated. The first objective, to minimize total FP water management cost (ManagementCost), is defined by equation 2.

$$ManagmentCost = \frac{(TC + IC + RC + DC)}{\sum_{i=1}^{I}\sum_{t=1}^{T} FP_{i,t}} \tag{2}$$

Total management cost, as depicted in Table 1, is defined as the sum of transportation cost (*TC*), injection cost (*IC*), relocation cost (*RC*), and desalination cost (*DC*). Transportation cost is not linearly related to transport distance (*d*); it is proportional to the sum of loading/unloading time and driving time. The *TRate* is the charge per hour of operation. The model assumes 30 minutes combined loading and unloading time regardless of transportation distance. Drive time is calculated assuming the average speed of travel for a truck in Weld County, which is 45 miles per hour.

$$TC = TRate * \left(\sum_{i=1}^{I} \sum_{t=1}^{T} \frac{FP_{i,t} * (1 - DP_{i,t})}{19[m^3/truck]} * \left(0.5[hrs./truck] + \frac{d}{45[mph]} \right) + \sum_{i=1}^{I} \sum_{t=1}^{T} \frac{FP_{i,t} * DP_{i,t} * (1 - RF_d)}{19[m^3/truck]} * \left(0.5[hrs./truck] + \frac{d}{45[mph]} \right) \right) \tag{3}$$

Total relocation costs during the modeled period (*RC*) are a function of how many desalination units must be moved to a new location at the beginning of each planning period (*M*) and the cost for each move as defined in Section 2.3 (*RRate*). Planning Horizon greatly impacts the need for relocation of treatment units and the degree of unit movement. Every time the locations of desalination units are optimized, there is a potential need to relocate units from an old location to a more profitable location. Thus, the shorter the planning horizon, the greater potential for desalination unit movement and high relocation costs.

$$RC = RRate * M \tag{4}$$

Injection cost (*IC*) is a function of the percent of water desalinated and the recovery factor of the desalination technology. A higher recovery factor lowers the need for injection. The cost of third party injection in Weld County is the *IRate*.

$$IC = IRate * \left(\sum_{i=1}^{I} \sum_{t=1}^{T} FP_{i,t} * (1 - DP_{i,t}) + \sum_{i=1}^{I} \sum_{t=1}^{T} FP_{i,t} * DP_{i,t} * (1 - RF_d) \right) \tag{5}$$

Desalination cost is a function of the volume of water treated and the number of desalination units purchased (*U*) (i.e. Total Treatment Capacity) with a fixed charge rate (*FCR*) as defined in Section 2.4.

$$DC = OPEX * \sum_{i=1}^{I}\sum_{t=1}^{T} FP_{i,t} * DP_{i,t} + FCR * CAPEX * U \tag{6}$$

The second objective, to maximize beneficial reuse, is defined by Equation 7. The number of desalination units purchased, and the recovery factor of the selected technology are directly related to the level of reuse achievable.

$$Reuse = \sum_{i=1}^{I}\sum_{t=1}^{T} FP_{i,t} * DP_{i,t} * RF_{d} \tag{7}$$

3. RESULTS AND DISUSSION

The impact of variable influent flowrate on capacity factor is unique to on-site FP water treatment and its influence on treatment cost was analyzed in detail. First, the concept of capacity factor was used to discuss the importance of UIC well scarcity to the viability of on-site FP water desalination and reuse. Next, several Pareto optimal FP water managements solutions are noted, followed by a discussion over the influence of key decision variables on capacity factor and on-site desalination cost. The following results are case specific but the highlighted trends are generally applicable to management of variable FP water flows at all on-site FP water treatment facilities. The work includes an open-source model that can be used to evaluate other case studies.

3.1 Influence of Transportation Cost

Before analyzing the results of multi-objective optimization for all the wells in Weld County, an intuitive understanding of the impact of transportation distance and UIC well availability/scarcity is developed by studying individual candidate desalination locations. The costs in Table 1 assume constant transportation distances and capacity factors among all wells. In reality, these variables are site specific. For any single candidate location, profitability of desalination increases as capacity factor increases and/or as injection transportation distance increases. When transportation cost is low, precise management and large capacity factors are required to make desalination profitable. Expressed differently, as transportation distance increases, the minimum required capacity factor (i.e. capacity factor target) for profitable operation decreases. This is shown in Figure 3 for three unique desalination technology/unit capacity combinations. v-AGMD is the cheapest desalination technology capable of achieving a large recovery factor (Table 1). The minimal capacity factors required during the deployment of a v-AGMD desalination unit of capacity of 10 m^3/d, 100 m^3/d, or 1000 m^3/d are presented in Figure 3A, 3B, and 3C, respectively. Similar trends are present for all the other technologies evaluated (Appendix B). Recall, from section 2.1, that transportation distance was calculated based on available trucking routes as roads do not go directly from wells to injection sites. Hence, there are candidate locations in Figure 3 that appear closer to disposal wells than the actual trucking distance.

In Figure 3, regions in dark blue show candidate locations that are most conducive to on-site treatment based solely on transportation distance and desalination cost. It is evident from the color gradients in Figure 3 that candidate locations farther from UIC wells do not require as large of a capacity factor to be profitable. Additionally, the cheaper the desalination technology, the lower the capacity factor required for profitability. The candidate locations in Figure 3c require minimum capacities in the range of 16%-53% compared to Figure 3a where only two candidate locations are profitable and only at capacity factors higher than 88%. Economies of scale make the desalination technology in Figure 3c cheaper and more profitable than the desalination technology in Figure 3a, assuming that the larger treatment units are operating at the same capacity factor as the smaller.

Assuming that any given treatment unit will operate at the same capacity factor is generally a poor assumption for on-site FP water treatment. Even among the wells requiring low capacity factors (darker blue), especially those in Figure 3c, there is no guarantee that the minimum capacity factor targets can be met under the constraints of FP water production. Even if a well is favorably located (far from any injection wells), there may simply not be enough, or any, FP water to desalinate in that location.

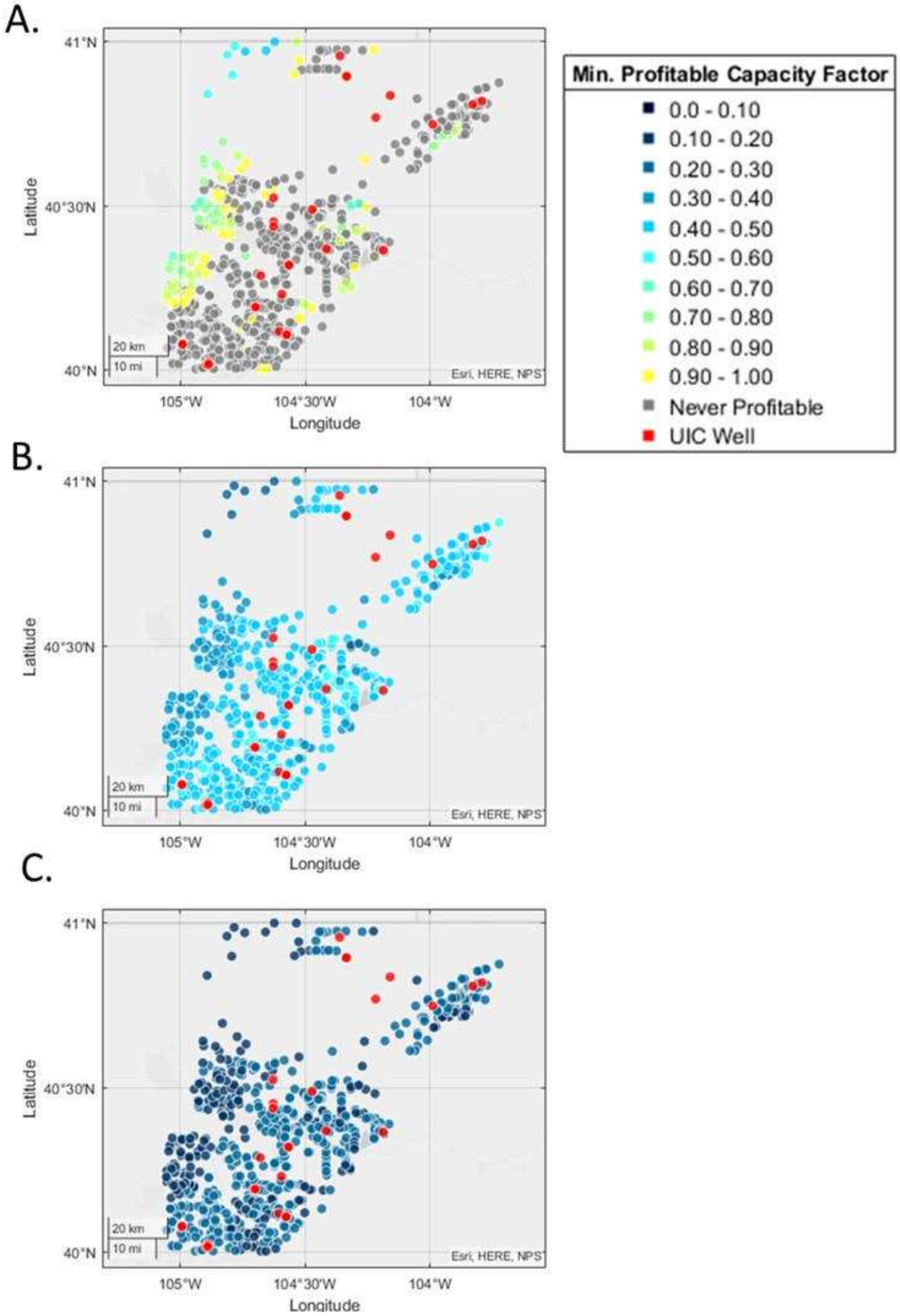

Figure 3: Candidate locations that have large enough transportation distances for desalination to be profitable, categorized by the minimum capacity factor that must be maintained to achieve a profit. (A) Desalination with v-AGMD at a capacity of 10 m^3/d. (B) Desalination with v-AGMD at a capacity of 100 m^3/d. (C) Desalination with v-AGMD at a capacity of 1000 m^3/d.

Likewise, although the 1000 m^3/d capacity units (Figure 3c) show lower required capacity factors (darker blue) than the 100 m^3/d capacity units (Figure 3b), a 1000 m^3/d capacity unit requires 100X more FP water to operate at the same capacity factor as a 100 m^3/d capacity unit; that volume of water may or may not exist at a particular candidate location at a particular time. Although a larger desalination unit appears better at first glance, it may not be optimal if FP water production is not large enough to justify the larger capacity. Therefore, there ought to be an optimal capacity that maximizes benefits from economies of scale while ensuring that the minimum capacity factors required for profitability can still be achieved or exceeded. The work that follows accounts for the temporal and spatial variability of FP water to find the optimal capacity and more generally the optimal FP water management plan.

3.2 Optimization

When integrating performance models with actual well data from Weld County, the evaluation of deployment and size of technologies results in multiple solutions and a Pareto frontier. The value of a Pareto frontier is holistically evaluating a solution that couples multiple design variables. All points on the frontier are equally 'good' and the exact optimum is dependent on partiality to one objective or the other. A set of optimal desalination management plans, plotted in the objective space of cost and reuse are distinguished from a select subset of all different management plans, by the Pareto frontier highlighted in orange (Figure 4a). The select subset of all solutions for Weld County is generated, in accordance with Section 2, from a sampling of unique combinations of the decision variables, Unit Treatment Capacity, Total Treatment Capacity, Planning Horizon, and Desalination Technology (MVC, RO, or MD), in the decision space. As highlighted in Figures 4b through 4e, the goal of this paper is to illustrate the effects of the decision variables, Planning Horizon and Unit Capacity, on the cost curve of each individual desalination technology. Management plans cheaper than 100% injection ($7.72 per m^3) are located below the horizontal dashed line labeled BAU. This cost represents the mean trucking and injection cost; BAU FP water trucking costs at individual wells are based on site specific transportation distances. The following paragraphs analyze two extreme solutions on the Pareto frontier, the best economic solution and the best solution for maximum reuse.

The best economic solution for Weld County regardless of water reuse preferences, in other words the cheapest solution, is to target 50% reuse with 100 m^3/d on-site RO units (minimum of the Pareto frontier, Figure 4a). Recall, the recovery factor of RO is assumed to be 57%. To achieve such a high level of reuse using RO almost all FP water (approximately 87%) must be treated at an on-site RO unit. Although MVC and MD have better recovery ratios and produce less brine per m^3 wastewater, the desalination cost associated with these technologies is too expensive to be offset by any additional reduction in bine transportation and injection cost. This result is specific to Weld County. As transportation distances increase, reductions in brine volume become more valuable and MVC and MD will become more favorable compared to RO.

Treating a majority of FP water with MD is the best solution for maximum reuse in Weld County. The cheapest management strategy (RO), only includes the beneficial reuse of approximately 50% of all FP water. Additional reuse is only achieved though increasing management cost. MD allows for reuse up to 85% because it has a maximum recovery factor of 88%. This makes MD the optimal treatment technology for maximum reuse. Approximately 83% of all FP water can be recovered by 100 m^3/d DCMD units at a comparable price to injection (Figure 4a), but the marginal cost to reuse an additional m^3 of FP water increases dramatically above 80% reuse as relocation costs increase and capacity factors decrease (Section 3.2.2). Some desalination technologies are never profitable above an appreciable level of reuse in Weld County, such as MVC.

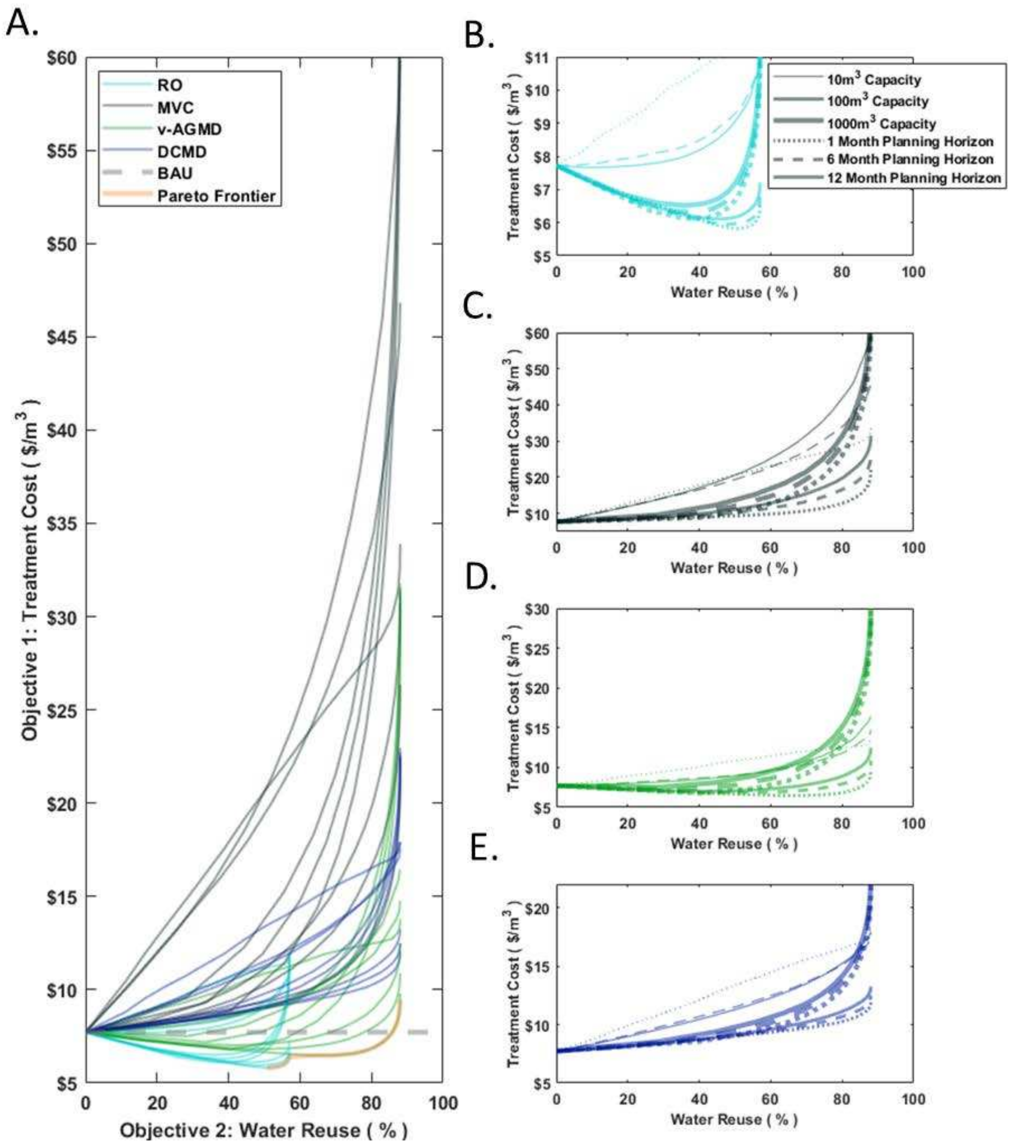

Figure 4: Solutions for a subset of all total management strategies is plotted in objective space (on cost vs reuse axes). Each line represents a unique combination of decision variables. A) Pareto optimal management strategies for Weld County, CO, highlighted in orange. B) Management strategies using RO. C) Management strategies using MVC. D) Management strategies using v-AGMD. E) Management strategies using DCMD.

MVC is not optimal because it is an extremely capitally intensive technology but, as transportation distances increase, it can be cheaper than injection. Life cycle assessment is outside the scope of this paper, but it should be noted MVC has a significantly lower specific energy consumption than MD which is desirable for lower carbon emissions when waste heat is not available. As the technology with the highest capital investment, it will also be very important for MVC to maintain a high capacity factor (section 3.2.1 and 3.2.3). An optimal treatment capacity (100 m^3/d), an optimal reuse target (dependent on management strategy), and an optimal planning horizon (~1 month) are visible in Figures 4b through 4e and will be addressed specifically in sections 3.2.1 through 3.2.3 respectively.

3.2.1 The Optimal Unit Treatment Capacity

From the decision variable Unit Treatment Capacity in Figures 4b through 4e, it is observed that independent of desalination technology, a 100 m^3/d treatment capacity is optimal. As suggested previously, this is because FP water production does not exist in high enough volumes to justify the extra capacity of a 1000 m^3/d unit that is not located at a centralized location. FP water data shows that only 13 out of 755 candidate locations have a large enough flow rate to sustain the minimum profitable capacity factor for a single deployed 1000 m^3/d capacity v-AGMD desalination unit during the month of April 2020 while 82 out of 755 candidate locations can support one unit of 100 m^3/d capacity even though it is more expensive at an equivalent capacity factor. The problem is exacerbated as reuse targets increase because the volumes of untreated FP water remaining at previously profitable locations are reduced; the second unit deployed to any given location will have less water available to treat than the first.

Treatment capacity can be reduced to achieve a high capacity factor, but this reduces economies of scale and increases relocation costs. Decreasing the unit treatment capacity without decreasing total capacity increases the number of units required which inherently increases the number of units requiring relocation (Section 3.2.2). Table 1 shows the impact of economies of scale on desalination cost. By decreasing v-AGMD system capacity from 1000 to 10 m^3/d, operating cost increases from 3.84 $/$m^3$ to 7.23 $/$m^3$. Assuming equal capacity factors, CAPEX also increases from 1.46 \$/m^3 to 3.93 \$/m^3. However, decreasing capacity means an inherent change in capacity factor. Figure 5 plots capacity factor against FP water reuse potential for several technologies of different unit capacities with a planning horizon of 1 month. Decreasing treatment unit capacity increases capacity factors for a given level of reuse as expected. This is especially true at high levels of reuse. Consider an older well producing a steady but small amount of FP water (Figure 2a). This well is unprofitable for desalination because the volume of FP water is low, but if high levels of reuse are to be met, the water must be desalinated. Having a smaller unit in locations like this would improve the average capacity factor. On the contrary if the only option for desalination is a treatment unit with a capacity of 1000 m^3/d there is no choice but to operate at a low and often unprofitable capacity factor. As determined previously, a treatment capacity of 100 m^3 per day appears to optimize this tradeoff between economies of scale, relocation cost, and capacity factor for Weld County (Figures 4b through 4c).

For the 100 m^3/d capacity treatment units, there is a correlation between capacity factor and CAPEX. The 100 m^3/d capacity treatment points do not coincide because the model deploys more capitally expensive units such as MVC favoring those locations with large FP water volumes where higher capacity factors can be achieved (Figure 5). When deploying desalination units in order of most profitable location, there is a tradeoff between deploying units to locations farthest from UIC wells and deploying units to locations where they can maintain the largest capacity factors (Section 3.2.4). Capitally expensive technologies like MVC favor large volumes of water to maintain high capacity factors while cheaper technologies like MD and RO favor longer transportation distances to capitalize on savings in transportation.

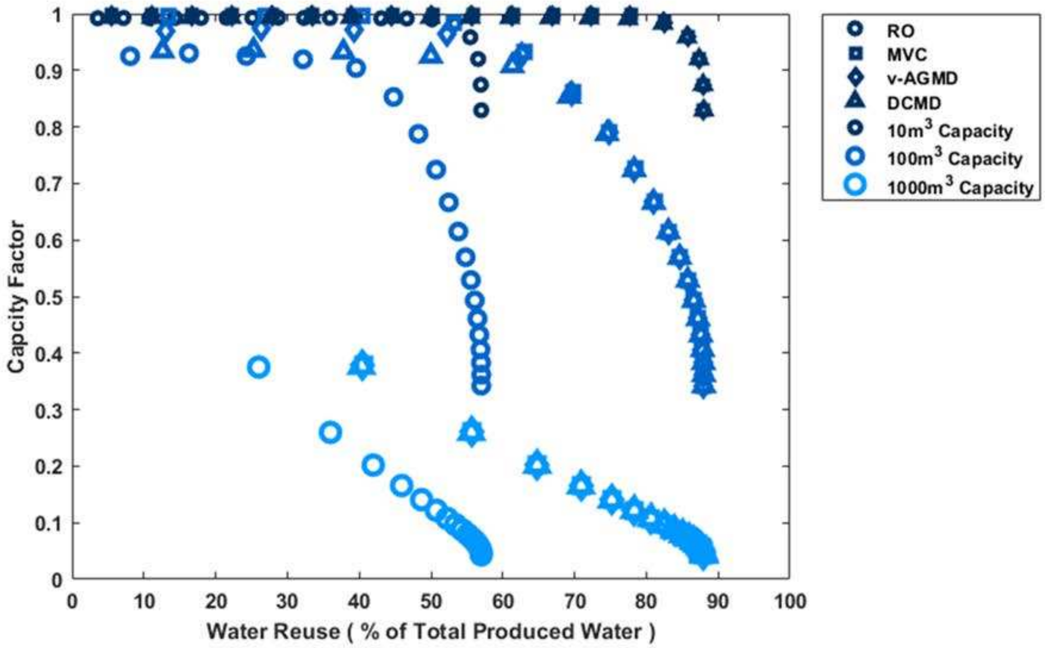

Figure 5: Capacity factor as a function of reuse for different desalination technologies.

3.2.2 The Optimal Reuse Target

Looking at cost as a function of water reuse in Figures 4b through 4e, there exists a unique optimal reuse target (i.e. the number of units purchased or total treatment capacity) for each desalination technology. For v-AGMD with a 100 m^3/d capacity (Figure 4d), it is approximately a 65% reuse target (corresponding to 250 units with a 25,000 m^3/d total capacity) and for RO at a 100 m^3/d capacity (Figure 4b) it is approximately a 51% reuse target (corresponding to 382 units with a 38,200 m^3/d total capacity). Because of the temporal and spatial variability of FP water, the marginal cost to reuse an additional m^3 of water is not constant for any given technology/unit capacity combination. This manifests in the non-linear relationship between reuse and cost in Figure 4a for any given technology/unit capacity combination and is the reason an optimal total treatment capacity exists.

It cannot be assumed that maximal reuse is optimal solely on the basis of desalination being cheaper than BAU when a constant capacity factor is assumed. There exists an optimal percent reuse, which is not the maximum achievable, because capacity factors decrease as water reuse approaches a maximum. Negative slopes in Figure 5 show declining capacity factors as percent reuse increases, regardless of unit capacity or desalination technology. Desalination must be implemented at more candidate locations, including those composed of wells with FP water flowrates lower than unit capacity, in order to achieve increased reuse. When the average capacity factor of the modeled desalination units is lowered, it takes more units to treat the same volume of water, increasing specific CAPEX.

Incremental increases to total treatment capacity (i.e. the number of desalination units) were evenly distributed in decision space. However, it can be seen from Figure 5, that each consecutive increase in total capacity (represented by each point moving from left to right along a curve) yields progressively smaller increases in reuse, because of declining capacity factors. For RO of 100 m^3/d capacity, increasing total treatment capacity from 0 to 1,000 m^3/d increases water reuse by 1.7% but increasing total treatment capacity from 38,000 to 39,000 m^3/d only increases water reuse by 0.5%. These diminishing returns contribute to the existence of an optimal reuse target. When targeting lower reuse, savings in transportation cost are not being realized but when targeting higher reuse, capacity factor falls off and desalination is being implemented at less and less profitable candidate locations. By not attempting to treat the FP water at less profitable wells, on-site desalination can be competitive.

3.2.3 The Optimal Planning Horizon

A decreasing capacity factor cannot be avoided as the reuse target increases but, optimizing the movement and deployment of treatment units minimizes the loss of capacity factor at the expense of increasing relocation costs. Figure 6 illustrates the relationship between planning horizon and capacity factor within this model and the case study of Weld County. Adjusting the planning horizon controls how often unit locations are sorted according to profitability which is directly related to how often there is a potential for relocation (section 2.5.1). Both capacity factors (Figure 6a) and relocation costs (Figure 6b) are plotted against planning horizon. In this manner capacity factor is indirectly related to total reallocation cost, plotted in Figure 6c. Capacity factor can be increased by decreasing the planning horizon (Figure 6a). This trend results from the increased profitability of operating units with high capacity factors as an incentive for increased relocation at the end of each planning period. Recall from Section 2.5.2, that relocation costs are neglected at the end of each planning period, when unit locations are sorted according to profitability, such that existing units are relocated to the most profitable locations, locations with high capacity factors. Likewise, as mentioned in Section 3.1 and investigated later in Section 3.2.4, locations farthest away from UIC wells are also more profitable. When relocation cost is accounted for, minimizing planning horizon is not always optimal because relocation cost increases as planning horizon decreases and units are moved more frequently to remain at the most profitable locations (Figure 6b). In other words, relocation cost increases as capacity factor is increased (Figure 6c). Recall, the goal is not to maximize capacity factor but to optimize the tradeoff between high capacity factor and low relocation cost. Figures 4b through 4e, show the impact of planning horizon on treatment cost. It is observed that, as expected, there is an optimal planning horizon. For v-AGMD, choosing the wrong planning horizon can add up to \$1.4 per m^3 or 17% to an otherwise optimal management strategy (Figure 4c). The optimal planning horizon is sensitive to relocation cost and varies within the range of potential relocation cost.

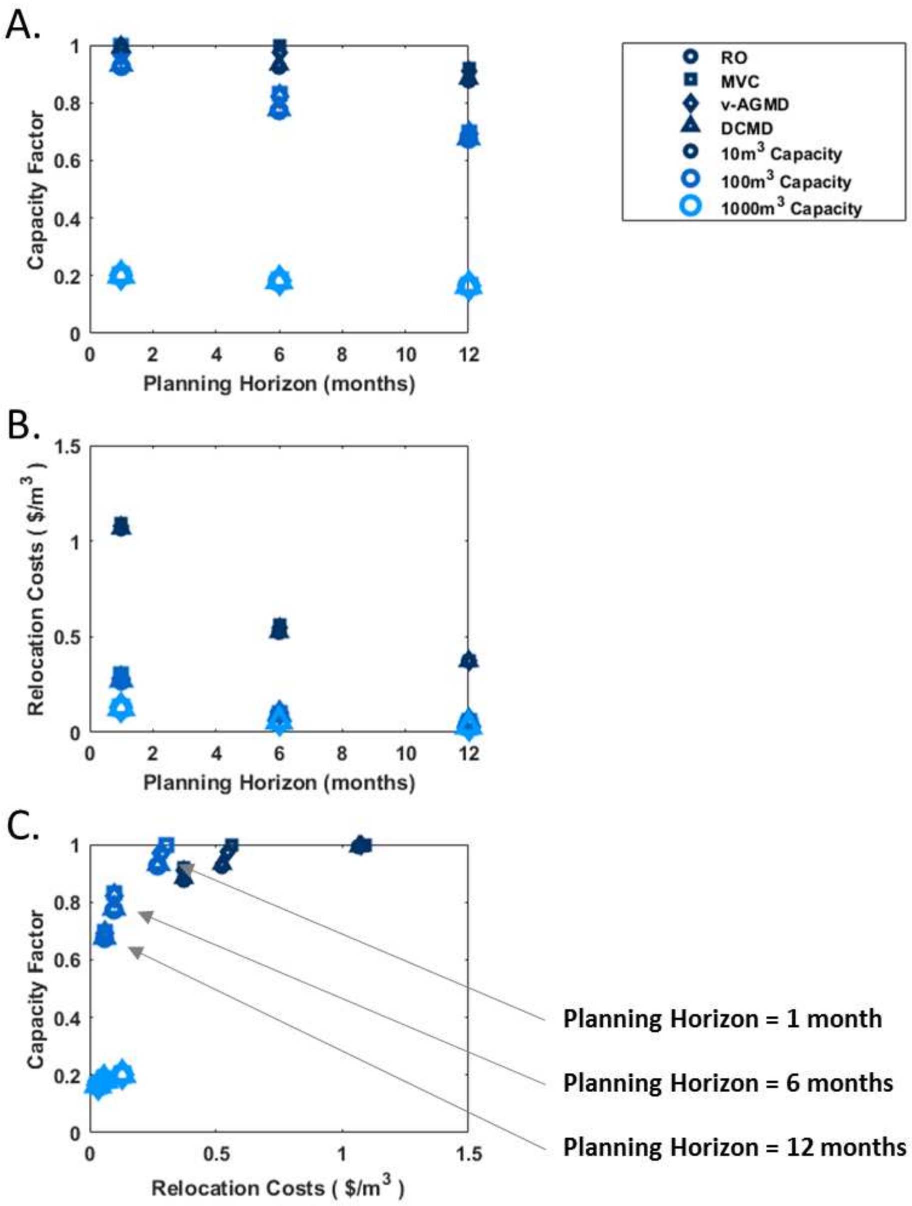

Figure 6: Relationship between planning horizon, movement, and capacity factor. A) Capacity factor as a function of planning horizon. B) Relocation cost as a function of planning horizon. C) Capacity factor as a function of relocation cost.

There is a great deal of uncertainty in relocation cost (section 2.3) which is addressed in Figure 7. The optimal planning horizon is a function of relocation costs, unit capacity, and desalination CAPEX. Figures 7a through 7d assume a \$3,000 relocation cost to be consistent with Figures 4b through 4e while Figures 7e through 7h assumes a high $10,000 relocation cost. For $3,000 relocation costs, it is generally less than one month (Figure 7a).

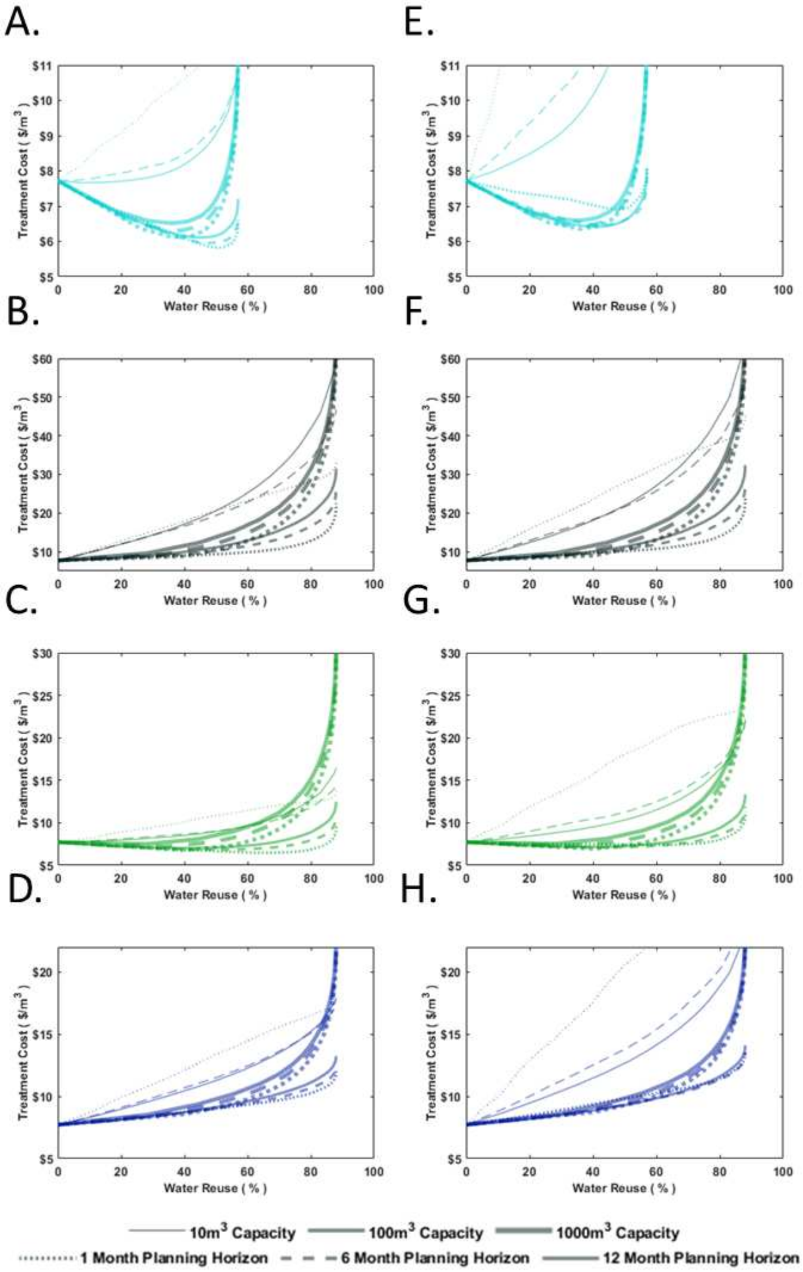

Figure 7: Treatment cost as a function of total water reuse for different planning horizons, technologies, and unit capacities. A-D) Relocation cost of $3,000 per unit. E-H) Relocation cost of $10,000 per unit.

When relocation costs are low (assumed to be $3000 per move as in Figure 4), it is generally optimal to move treatment units as often as possible (assumed here to be every month) to keep them in the most profitable locations. The exception is for technologies with small capital investments and small capacity units such as MD and RO of 10 m^3/d capacity. Maintaining a high capacity factor is not as important for these technologies and excessive relocation is frivolous, leading to longer planning horizons being optimal. As relocation costs increase, it becomes preferable to accept lower capacity factors to avoid paying to move units frequently. For assumed $10,000 relocation costs, the optimum planning horizon is generally still close to 1 month (Figures 7e-7h) but for technologies with small capital investments like RO and DCMD, the optimal planning horizon increases.

3.2.4 Implementation of a Management Strategy in Weld County, CO

To provide detailed insight into an optimal management strategy built according to the principles discussed previously, implementation of the cheapest management plan in Weld County is observed through select candidate locations. Figure 8 offers a visual representation of a management strategy, through 8 select candidate locations as the targeted level of reuse increases from 37% to 51% (optimal) using RO units with 100 m^3/d capacities and a one month planning horizon. The dashed blue line represents treatment capacity. Treatment capacity shows the number of treatment units in operation during any given month. At candidate location 722 in May 2019, when a total of 212 desalination units are deployed in Weld County, there are 5 desalination units in operation (Figure 8 left). The solid blue and green represent the fractions of total FP water treated and injected respectively.

Recall from Figure 2, the profile of FP water flowrates can signify a well's age. Candidate locations composed of old wells do not have a high monthly variation in flow (candidate locations 320 and 500 in Figure 8). Low flows often make these well unlikely choices for desalination (candidate location 500) but when enough wells are clustered within a quarter mile radius, they can produced enough water to be optimal candidates for desalination because of their steady flows (candidate location 320). Young wells experience a sharp decline in FP water flow during the first 6 months of operation (candidate locations 691, 700, 720, 722, 736, and 743 in Figure 8). The wells at candidate locations 700 and 743 did not produce much water in their first month of operation (Figure 8). It is likely that these wells started producing part way through that month. The profile of FP water flowrates sheds light on the mechanics of an optimal management strategy.

Starting with a lower level of reuse (37%), desalination is first prioritized at the most profitable candidate locations such as candidate locations with high capacity factors (candidate locations 320, 691, 720, 722, and 743 in Figure 8). However, even if a capacity factor of 1 could be achieved in a given location (area ‘A’ in Figure 8), desalination is sometimes conducted elsewhere where disposal distances are greater. Note that in the month of October 2019 desalination at candidate location 700 (would be capacity factors =1) is considered less profitable than desalination at candidate locations 720 and 736 (capacity factors <1) because of longer disposal distances at the latter (Figure 8). Neglecting relocation cost, it is estimated that desalination at candidate location 736 in the month of July 2019 is 3.12 $\$/m^3$ cheaper than injection while at candidate location 700 desalination would only be 2.55 $\$/m^3$ cheaper than injection. The capacity factor at candidate location 736 is only 40%, but the transportation cost associated with injection would is 2.52 $\$/m^3$ more expensive than candidate location 700. The capital cost of a technology impacts this tradeoff. Cheaper technologies like RO can justify lower capacity factors while expensive technologies like MVC are more impacted when capacity factor is lowered.

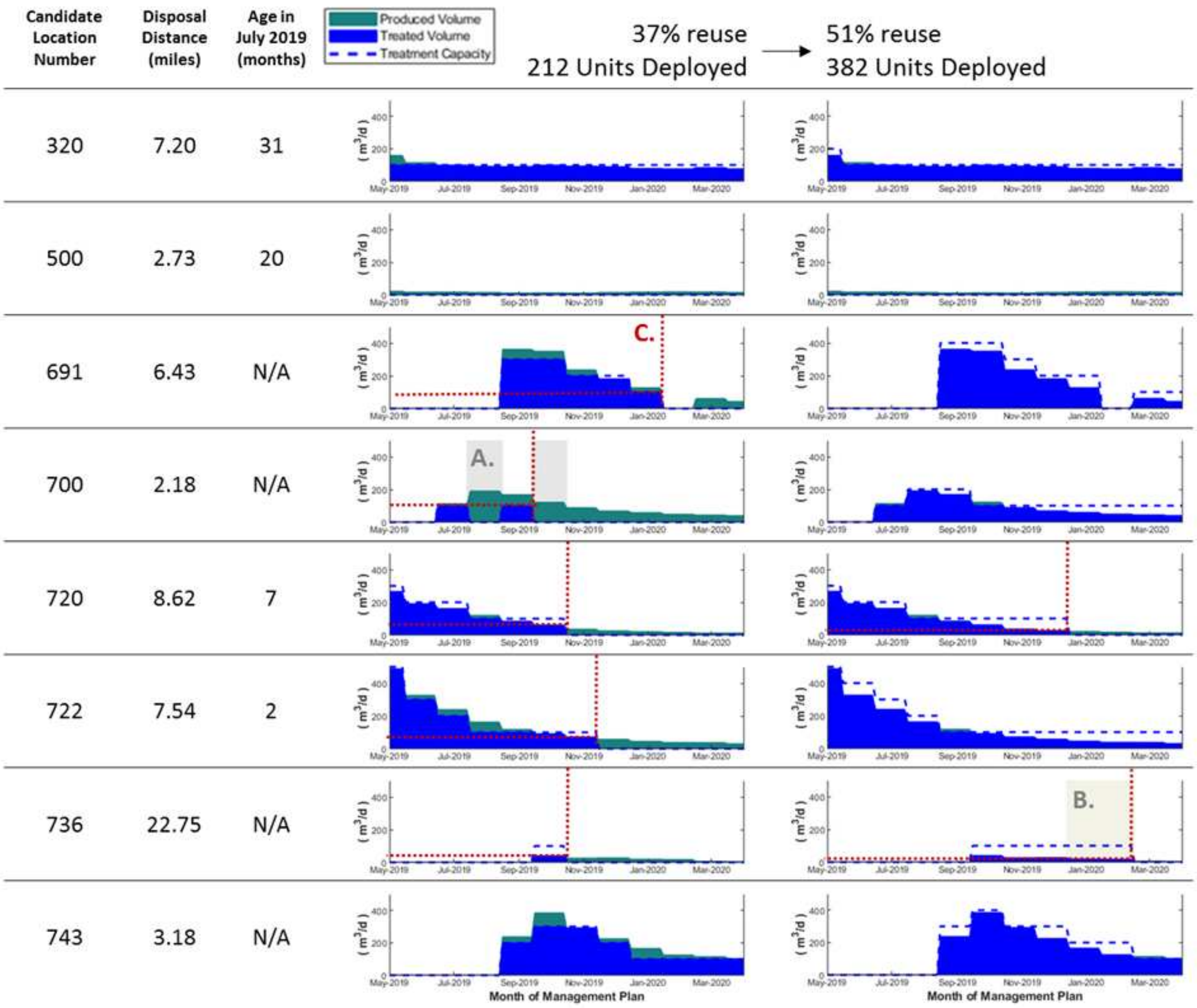

Figure 8: Implementation of a Management Strategy (RO of 100 m^3/d capacity) in Weld County, CO at 8 select candidate locations. A) No treatment when capacity factor would be equal to 1 for at least one treatment unit. B) Treatment even when capacity factor of the last unit deployed is lower than 25%. C) The time and flow rate after which desalination generally stops indefinitely for a cluster of wells.

Moving from 37% to 51% reuse (the optimal), RO units are added to the remaining candidate locations with the highest capacity factors and/or the longest transportation distances and treatment is expanded at candidate locations 320, 691, 700, 720, 722, 736, and 743 to meet the increased demand for water reuse. This increase in reuse causes the flowrate after which desalination stops at a candidate location (represented by red dashed line ‘C’) to decrease (Figure 8). For instance, the flowrate cutoff for desalination deployment drops from 62 m^3/d to 21 m^3/d corresponding to capacity factors of 62% and 21% respectively for candidate location 720. As the reuse target increases to 51%, desalination becomes necessary in less profitable locations. For RO units of 100 m^3/d capacity to be profitable in treating FP water in Weld County, a capacity factor must generally remain greater than 15% on average depending on the distance to the nearest injection well. Recall from Figure 4, that RO units of 100 m^3/d capacity are most profitable when targeting approximately 50% reuse. In Figure 8, a majority of desalination units are operating well above 15% capacity when operating at 37% reuse signifying that additional units can be placed to increase profits. Most desalination units are operating at or above 15% capacity when targeting 51% reuse, but few could be added that would further increase capacity factors. At 51% reuse, desalination becomes required at candidate locations 691, 700, 736, and 749 when the capacity factor is sometimes less than 25% (area ‘B’ in Figure 8). Targeting reuse greater than 51% will lead to the addition of more treatment units operating at unprofitable levels.

4. CONCLUSIONS

This work constitutes the first systems level techno-economic analysis of flowback and produced water desalination with mobile packaged treatment modules to account for the impact of variable water flowrates and a need for a method of module movement and redeployment. There is an optimal planning horizon for deployment, an optimal packed unit capacity, and an optimal water reuse target when considering a FP water management strategy for Weld County, Colorado. All these trends can be explained by tracking changes to capacity factor, unit movement, and the number of units deployed. Annualized capital expenditures decrease as capacity factor increases but there are costs associated with achieving a high capacity factor by decreasing unit capacity and planning horizon. Specifically, relocation costs are increased and economies of scale are sacrificed to achieve large capacity factors. For Weld County, the optimal packaged desalination unit has a 100 m^3/d capacity regardless of desalination technology, and its deployment should be reevaluated every 1-6 months. To be competitive with injection without additional storage to hold water for later desalination, the maximum reuse potential in Weld County is 50-60%. Other basins will have unique optimal management strategies even when defined within the context of this paper. The relationship between increasing capacity factor and operational cost is dependent on the characteristics of the shale site.

4.1 Limitations and Future Work

Although this work is limited in regards to simplistic labor and relocation cost estimates as well as the omission of additional storage potential, it represents a significant advancement in the field as it accounts for the impact of variable FP water flowrates on desalination costs with mobile packaged treatment units. A key difference between an on-site and centralized management approach that has not been previously addressed is that a centralized wastewater treatment plant can be custom built for a predicted design flowrate. This is not possible considering the extremely variable nature of FP water. It is not reasonable to build thousands of custom built small scale treatment units, so in this study packaged units of 10, 100, and 1000 m^3/d are considered. For simplify, only a single size unit capacity was considered at a time. Already, the results convey a need to consider design capacity in the design process to maximized tradeoff between capacity factor, relocation costs, and economies of scale. Future work should continue to explore and attempt to convey the importance of design capacity to the experimental community. For example, treatment cost could potentially be reduced from those reported here, specifically at high levels of reuse, by incorporating the option to switch from use of 1000 m^3/day units in times of very high flows to $10m^3/day$ units as flows decay.

A problem inherent from using packaged plants of a specific capacity is that the actual flow rate of FP water at a particular location may be slightly larger than the designed treatment capacity of a unit. Addressed in this paper, two solutions to this problem are to add another treatment unit of equal size or to inject the remaining water. However, another solution is to simply buy additional storage as opposed to the solutions addressed in this paper. Future work should investigate the use of additional storage capacity as a substitute for additional treatment capacity or injection. Again, treatment cost could potentially be reduced from those reported here, specifically at high levels of reuse, by purchasing additional storage as opposed to additional treatment capacity during a given time period. For example, larger storage capacities can be used to reduce variation in FP water flows allowing for less relocation and higher capacity factors.

This paper makes a first attempt to quantify a previously neglected cost of on-site desalination, relocation cost. Uncertainty is introduced through the inclusion of relocation costs. FP water volumes are collected on a monthly basis. The model suggests that if relocation costs are low enough, a planning horizon less than one month may be optimal, but shorter planning horizons cannot be studied due to limitations in data availability. There is uncertainty in relocation costs themselves that are especially great when considering short planning horizons. It is likely that relocation cost will be related to the total number of units relocated within the same time frame. The model assumes that there is no limit to the number of units that can be shipped and installed simultaneously. For simplicity, units are moved during the first week of a calendar month and their capacity is assumed available immediately upon relocation while in reality there will be a 1-7 day installation period (Queensland Government, Mohammad-Pajooh et al., 2018). This installation and maintenance period will reduce the maximum attainable capacity factor of a unit and decrease overall water treatment capacity of the whole system. To build upon this first attempt at quantifying relocation cost, it should be verified that relocating treatment units can be feasibly conducted in this manner especially at the shorter planning horizons that the current model suggests might be optimal. Regardless, the results already show the importance of relocation costs, specifically when the distance to an injection site is short. Attention to size, weight, and mobility should be incorporated into the design process of future potential on-site desalination technologies.

There is additional uncertainty in labor cost which makes up a large portion of desalination operating cost. Estimates of the economies of scale for labor in this paper are conservative. They were estimated under the assumption that each desalination unit is an isolated system while in reality they are not. Commute time across Weld County is typically less than one hour; it is feasible for one work crew to manage and service multiple desalination units. While some economies of scale will still exist, there are still more units to service when unit capacity is smaller, the ability of a work crew to manage multiple units dampens the effect. Labor cost are also sensitive to the degree of automation and instrumentation. A more optimistic estimate of labor cost will reduce the economic penalty on small capacity desalination units.

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APPENDIX A: Economic Equations

Some equipment costs in literature were published up to 12 years ago. They were converted to 2018 dollars using the Chemical Engineering Plant Cost Index (CEPCI) using equation A1 where C is the equipment cost in 2018 dollars and C_{ref} is the published reference cost.

$$C = C_{ref}\left(\frac{Cost\ index\ for\ 2018}{Cost\ index\ when\ published}\right) \tag{A1}$$

The capacity method was used to scale equipment cost for whenever published data for a specific capacity was not available using equation A2 where C is the equipment cost at the desired capacity, C_{ref} is the published reference cost, K is the desired capacity, K_{ref} is the published reference capacity, and m is the degression coefficient.

$$C = C_{ref}\left(\frac{K}{K_{ref}}\right)^{m} \tag{A2}$$

Specific capital cost ($CAPEX$) is calculated by defining a fixed charge rate (FCR) and capacity factor (CF) using equations A3-A6 based on the methods used by NREL’s Annual Technology Baseline (NREL, 2020).

$$CAPEX = \frac{FCR * CAPEX}{CF * Capacity * 365} \tag{A3}$$

CF is the average capacity factor during a year of operation where V is the volume in m^3 of water treated during a year of operation and K is the capacity of a desalination unit in m^3/d.

$$CF = \frac{V}{K * 365} \tag{A4}$$

FCR is the cost, per dollar of investment, incurred annually for an operator to pay the carrying charges on their investment where *IRR* is the internal rate of return, *t* is the lifetime of the investment, *TR* is the tax rate, and *PVD* is the present value of depreciation.

$$FCR = IRR * \left(\frac{1}{1 - \frac{1}{(1 + IRR)^t}} \right) * \left(\frac{1 - TR * PVD}{1 - TR} \right) \tag{A5}$$

PVD is defined by equation A5 where *i* is inflation rate and *MACRS DF* is the depreciation faction during year *y*.

$$PVD = \sum_{y=1}^{7} \left(MACRS\ DF * \left(\frac{1}{\left((1 + IRR) * (1 + i)\right)^y} \right) \right) \tag{A6}$$

Table A1: Economic Inputs

Cost of Steam	0.008	\$/kg
Cost of Electricity	0.069	\$/kWh
FP Water TDS	30000	mg TDS/L
Cost of Injection	4.09	\$/m3
Transport Cost	105	\$/hr
Unit Lifetime	20	years
Internal Rate of Return	10%	
Inflation Rate	0%	
Tax Rate	5%	

APPENDIX B: Supplemental Results

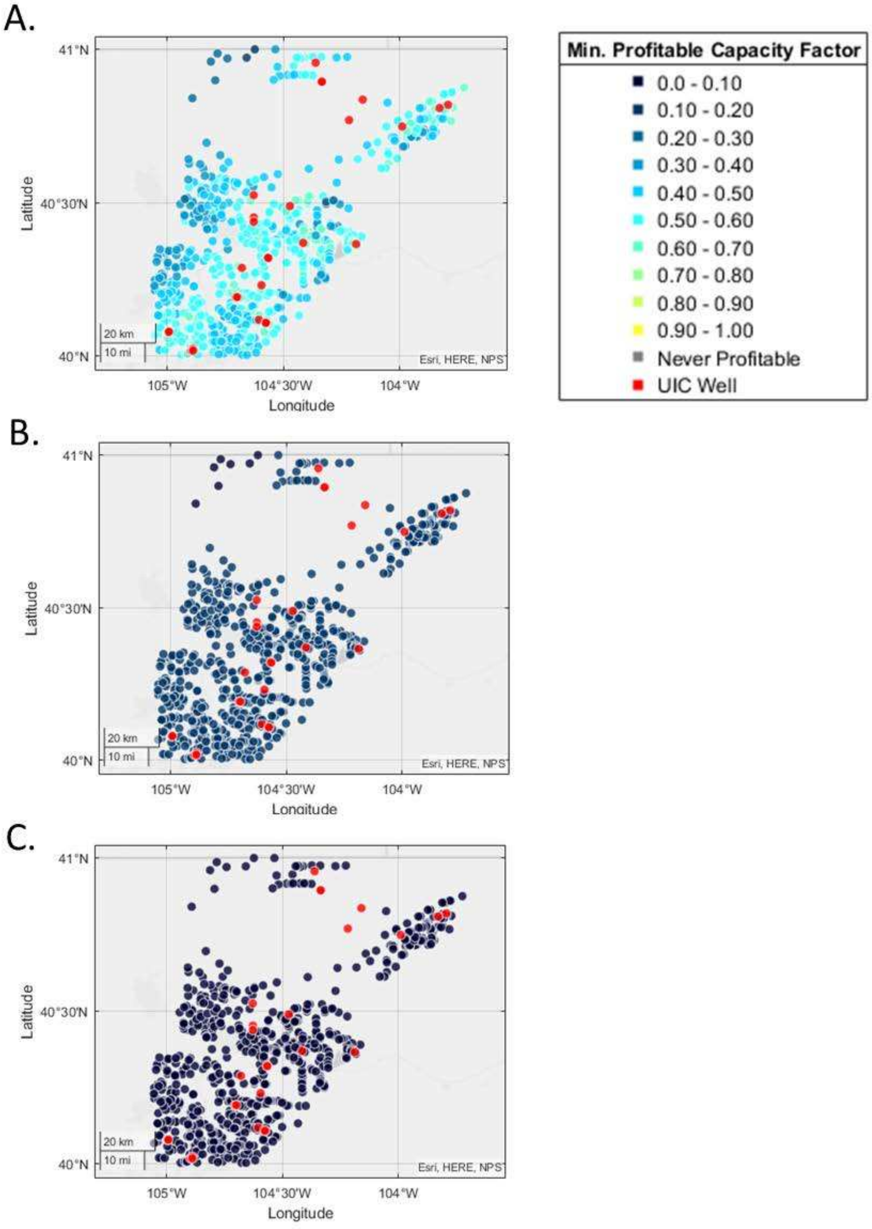

Figure B1: Candidate locations that have large enough transportation distances for desalination to be profitable, categorized by the minimum capacity factor that must be maintained to achieve a profit. (A) Desalination with RO at a capacity of 10 m^3/d. (B) Desalination with RO at a capacity of 100 m^3/d. (C) Desalination with RO at a capacity of 1000 m^3/d.

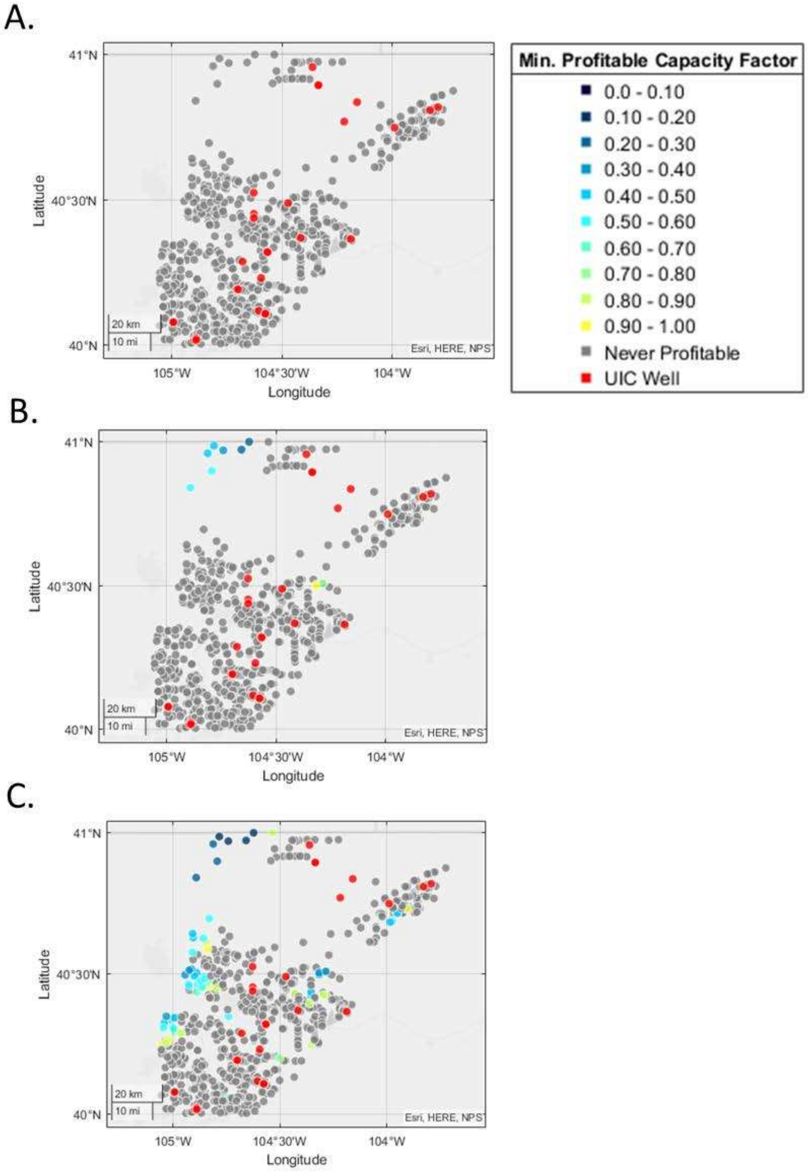

Figure B2: Candidate locations that have large enough transportation distances for desalination to be profitable, categorized by the minimum capacity factor that must be maintained to achieve a profit. (A) Desalination with DCMD at a capacity of 10 m^3/d. (B) Desalination with DCMD at a capacity of 100 m^3/d. (C) Desalination with DCMD at a capacity of 1000 m^3/d.

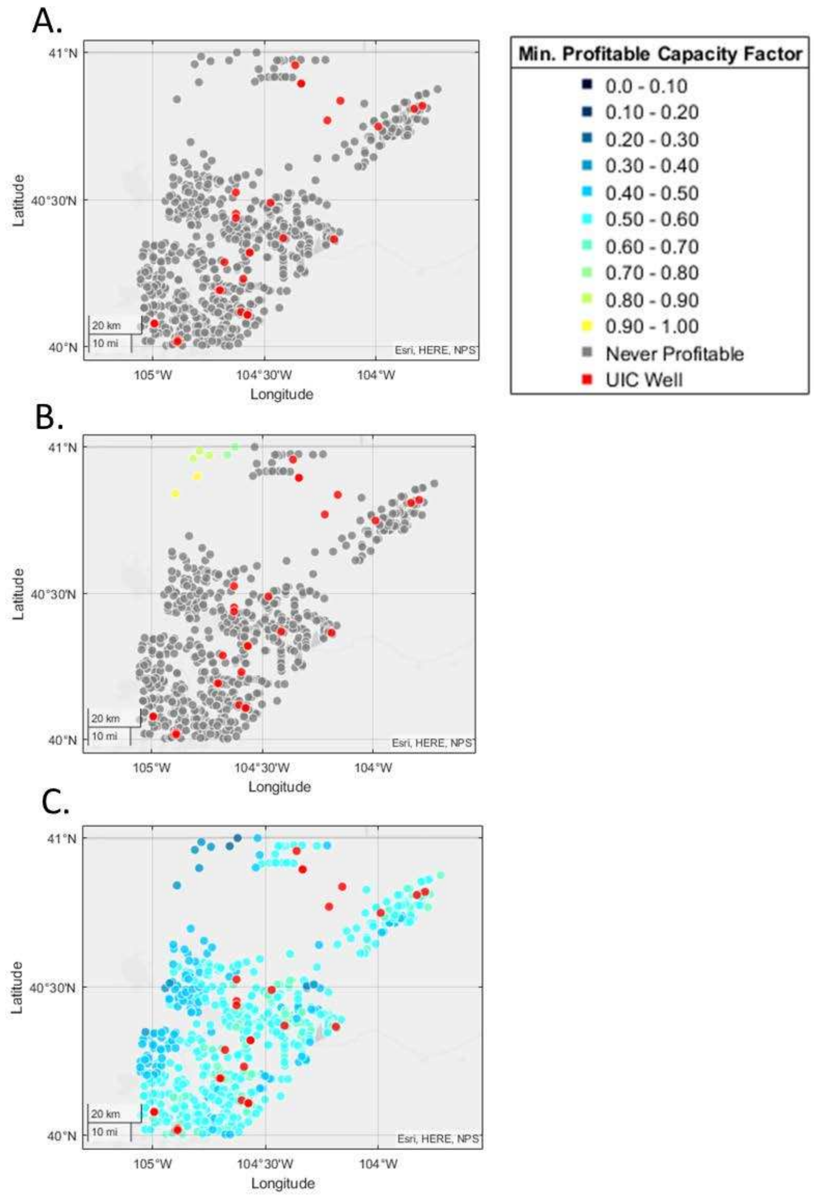

Figure B3: Candidate locations that have large enough transportation distances for desalination to be profitable, categorized by the minimum capacity factor that must be maintained to achieve a profit. (A) Desalination with MVC at a capacity of 10 m^3/d. (B) Desalination with MVC at a capacity of 100 m^3/d. (C) Desalination with MVC at a capacity of 1000 m^3/d.

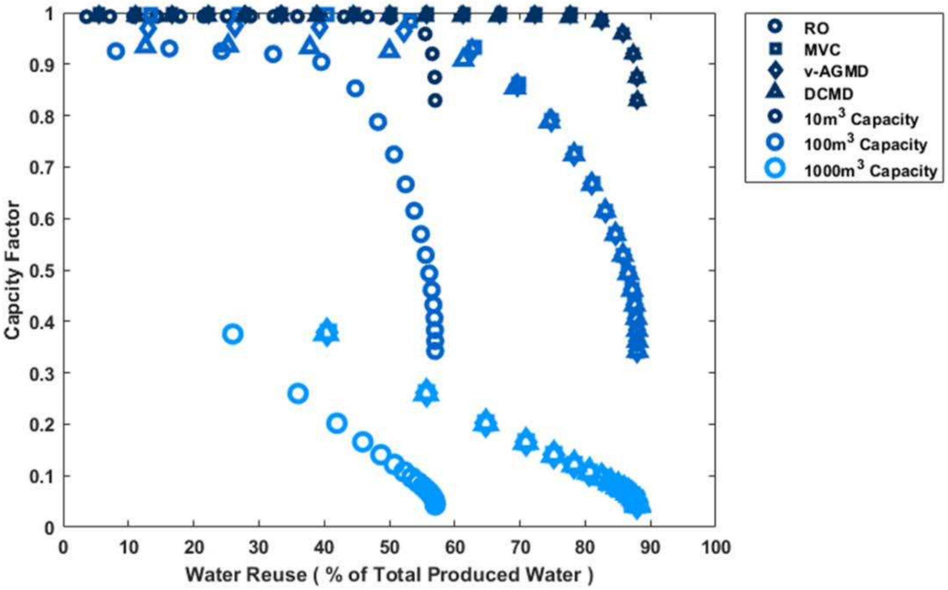

Figure B4: Sensitivity to relocation cost: Relocation cost = $10,000 per move. Capacity factor as a function of reuse for different desalination technologies.

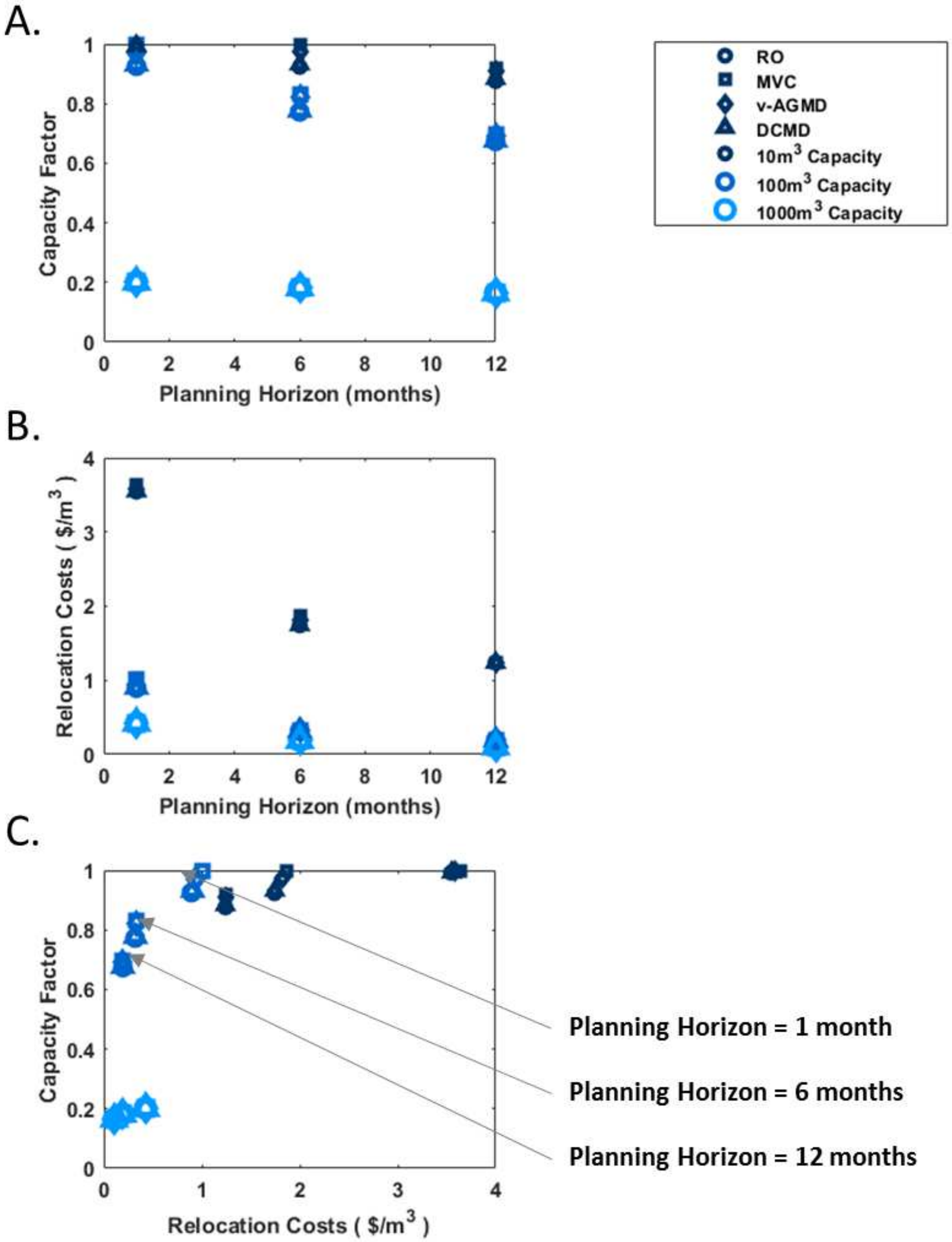

Figure B5: Sensitivity to relocation cost: Relocation cost = \$10,000 per move. Relationship between planning horizon, movement, and capacity factor. A) Capacity factor as a function of planning horizon. B) Relocation cost as a function of planning horizon. C) Capacity factor as a function of relocation cost.