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Concept Paper

Evaluation of a Minimum Liquid Discharge (MLD) Desalination Approach for Management of Unconventional Oil and Gas Produced Waters with a Focus on Waste Minimization

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Abstract: The objective of this research study was to evaluate the feasibility of using a minimum liquid discharge (MLD) desalination approach as an alternate management option for unconventional produced waters (PWs) with a focus on minimizing the generation of solid waste. The feasibility of MLD was evaluated using OLI, a water chemistry software, to model thermal desalination of unconventional PWs from the Delaware Basin in New Mexico (NM). Desalination was theoretically terminated at an evaporation point before halite (NaCl) saturation in the residual brine. Results of this study showed that selectively targeting a subset of higher flow rate and lower TDS wells/centralized tank batteries (CTBs) could yield up to 76% recovery of distillate while generating minimal solid waste. Using a selective MLD approach did reduce the quantity of distillate recovered when compared with ZLD, and left a reduced volume of residual brine which has to be managed as a liquid waste. However, selective MLD also greatly reduced the amount of solid waste. The use of a ZLD approach yielded incrementally greater quantities of distillate but at the cost of large quantities of difficult-to-manage highly soluble waste. Simulation results showed that waste generated before NaCl precipitation was primarily composed of insoluble compounds such as calcite, barite and celestite, which can be disposed in conventional landfills. This study also found a simple empirical linear relationship between TDS and distillate recovery, thus allowing a non-expert to rapidly estimate potential distillate recovery for a given starting PW quality.

Keywords: produced water treatment; thermal desalination; minimum liquid discharge (MLD); beneficial use; solid waste minimization; halite precipitation

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1. Introduction

Unconventional Oil & Gas (O&G) operations across the US, including the Delaware Basin in New Mexico, are expected to generate large quantities of produced water (PW). Currently, the O&G industry has two options for managing PW, which may be termed as business-as-usual or baseline options. These two options are (1) injection into salt water disposal (SWD) wells and (2) minimal treatment to produce a clean brine followed by its reuse in on-going O&G operations. An alternate option which envisages the use of desalinated PW for various beneficial purposes within the O&G industry (e.g., cooling water) and/or outside the O&G industry (e.g., surface discharge, agriculture use) has recently gained increased attention [1]. The drivers for this increased attention include potential constraints to the abovementioned baseline options and/or alleviation of regional water scarcity, which can be achieved by either substituting industry withdrawals of fresh and brackish water with recovered distillate and/or augmenting local freshwater supplies. Any potential risk arising from the use of distillate within the O&G industry can be considered low, given that the distillate will not be introduced into the environment. However, lack of adequate information on PW and distillate composition was stated to be a major factor that could prevent beneficial use of distillate outside the O&G industry [2].

Desalination of PW has several challenges including high energy requirements, potential toxicity associated with organics in the desalinated PW and generation of large quantities of highly soluble solid waste. In a recent study, it was estimated that desalination of approximately 500,000 bbl/d containing 295,500 mg/L total dissolved solids (TDS) to 80% evaporation by volume would generate approximately 0.31 M lb/d of sparingly soluble waste (primarily gypsum and celestite) and 31.5 M lb/d of NaCl (5.75 M tons/year) [3]. For comparison, annual US salt production in 2020 was 39 M tons, and salt production from the desalination of 500,000 bbl/d PW would equal approximately 15% of US production [4]. If run in a zero liquid discharge (ZLD) mode by complete evaporation of the residual brine, an additional 15.8 M lb/d of mixed waste would be generated. Further, with the exception of gypsum and celestite, most of the solid waste generated (>99% by mass) was comprised of highly soluble salts such as NaCl. The generation of such large quantities of difficult-to-manage, highly soluble solid waste is considered to be a major challenge for the implementation of desalination of unconventional PWs.

According to a recent report, the volume of water used for fracturing by the O&G industry in New Mexico was 311.4 M bbl/yr (0.85 M bbl/d) and PW generated was 1240 M bbl/yr (3.4 M bbl/d) in 2019 [5]. The same report citing NM Oil Conservation Division data [6] stated that the source of water for fracturing operations in Eddy and Lea counties (November and December 2020) was 13, 47 and 40% from fresh (TDS < 1000 mg/L), brackish (TDS between 1000 and 10,000 mg/L) and PW, respectively. Assuming that operations in Eddy and Leah counties are approximately representative of state-wide unconventional O&G operations in NM, total fresh and brackish water used by the O&G industry in NM (in 2019) would be approximately 111,000 and 400,000 bbl/d, respectively. While current water use is likely higher than in 2019, a sufficiently large quantity of PW is available in NM such that enough PW can be desalinated to either substantially or completely offset industry withdrawals of fresh and brackish water in NM, leaving these resources for use by local consumers.

1.1. Concepts—Minimum vs. Zero Liquid Discharge

The main difference between minimum liquid discharge (MLD) and ZLD zero liquid discharge (ZLD) desalination options is that MLD seeks to minimize solid waste generation at a lower water recovery when compared with ZLD, which seeks to maximize water recovery but also generates large quantities of difficult-to-manage solid waste (primarily NaCl, in the case of desalination of unconventional O&G PWs) [7,8]. Panagopolous and Haralambous [9] noted that for seawater desalination (TDS—35,000 mg/L), an MLD process recovered up to 95% freshwater (distillate) at an energy consumption of 5.4 kWh/m^3 whereas a ZLD system was able to recover up to 100% freshwater but required almost twice the energy input of an MLD system (10.43 kWh/m^3). Therefore, from the perspective of energy consumption and waste generation, MLD systems with lower water recovery can be more attractive than ZLD systems.

If distillate obtained from desalination of PW is used within the O&G industry, it may not require further treatment as environmental aspects/concerns typically associated with internal use may not pose an issue. However, significant research is required before distillate can be beneficially used outside the O&G industry. PW can vary both spatially and temporally [2] and therefore, the composition of distillate obtained from varying PW quality may be expected to vary as well. Environmental concerns regarding distillate use for beneficial purposes outside the O&G industry is mostly centered on the composition of organic compounds that can partition into the distillate as a result of desalination. Therefore, the composition of the organics present in distillate and potential toxicity considerations, if any, will have to be determined prior to beneficial use. Physico-chemical as well as biological treatment technologies can be employed to remove/destroy organics present in distillate and reduce any residual organics to within regulatory compliance limits. Note that the characterization of distillate obtained from desalination and evaluation of any potential toxicity for beneficial use outside the O&G industry is not within the scope of this research study.

1.2. Objectives of Research

As noted in the discussion above, the objective of this case study was to use an MLD approach to estimate distillate recovery via desalination of unconventional PWs, where the desalination process was terminated at the point just prior to halite (NaCl) saturation.

Specific tasks associated with this study are noted below.

1. Develop a conceptual desalination process using OLI water chemistry software [10] that allows identification of the evaporation point at which the residual brine is saturated with NaCl;
2. Estimate total solid waste generation prior to NaCl precipitation;
3. Determine if a simple correlation can be used to predict distillate recovery.

2. Materials and Methods

2.1. Produced Water Quality Used in OLI Modeling

General water quality parameters and major ions for 83 wells and/or centralized tank batteries (CTBs) from XTO operations in NM are summarized in Table 1 below. Given that the objective of this research effort was to predict the point of NaCl precipitation, only major ions listed in Table 1 below were considered for input to the OLI model. As a quality control check, the cation-anion balance for each PW quality was calculated; this balance was generally within a relative percent difference of 30%. Average TDS and flow rate for the 83 wells/locations dataset were approximately 209,000 mg/L (range of 39,000 to 310,000 mg/L) and 800 bbl/d (range of 3 to 7000 bbl/d), respectively.

Table 1. Summary of produced water quality used in this study (from XTO operations in NM).

	Water **bbl/d**	**TDS** **mg/L**	**pH** **su**	**Na** **mg/L**	**K** **mg/L**	**Ca** **mg/L**	**Mg** **mg/L**	**Sr** **mg/L**	**Ba** **mg/L**	**Fe** **mg/L**	**Mn** **mg/L**	**Li** **mg/L**	**Cl** **mg/L**	**Br** **mg/L**	**SO_4** **mg/L**	**HCO_3** **mg/L**
Delaware Formation (40 wells)																
Average	1017	248,785	6.4	64,015	1707	24,110	2980	1089	4	33	7	36	156,227	1366	194	127
Median	522	262,363	6.3	67,805	1899	27,965	3304	1141	4	28	7	40	165,282	1492	112	49
Min	11	38,903	5.0	13,307	209	341	70	92	0	0	0	12	22,200	41	41	12
Max	7000	355,107	7.4	83,690	2529	31,656	4137	1903	11	80	17	53	253,125	2467	664	805
Bone Springs/Bone Sands Formation (35 wells)																
Average	392	169,091	6.6	54,022	1231	8484	1230	448	2	31	2	68	104,065	1000	395	411
Median	196	154,574	6.6	56,552	1259	5216	774	296	1	27	1	56	94,292	898	357	244
Min	9	44,225	5.5	15,380	209	405	69	102	0	1	0	12	26,579	196	90	12
Max	3000	268,913	7.5	73,018	1763	31,793	3491	1309	9	76	15	129	169,486	1855	1420	952
Devonian Formation (3 wells)																
Average	2857	259,374	5.7	62,978	2070	27,169	3341	1349	3	31	8	34	164,210	1786	261	24
Median	2551	255,565	5.5	62,080	1952	27,659	3210	1518	4	31	7	38	162,654	1786	158	24
Min	19	234,664	5.5	56,039	1706	25,070	2798	937	3	27	7	23	145,567	1546	107	12
Max	6000	287,894	6.2	70,817	2552	28,777	4017	1591	4	34	8	42	184,408	2025	517	37
Upper Avalon Formation (3 wells)																
Average	104	213,433	6.4	70,500	1569	11,130	1825	507	1	36	4	52	127,822	1366	880	728
Median	36	213,631	6.4	70,394	1626	9735	1625	534	2	22	4	46	128,021	1366	880	878
Min	3	205,074	6.1	66,935	1432	5004	1168	220	0	20	1	44	125,574	1251	786	220
Max	274	221,594	6.6	74,172	1649	18,652	2681	766	2	66	5	67	129,872	1481	973	1086
Wolfcamp Formation (2 wells)																
Average	1324	77,139	6.8	25,678	609	2394	388	596	3	15	0	52	47,659	336	208	195
Median	Not applicable															
Min	1200	70,784	6.5	22,760	585	2151	300	548	3	6	0	35	44,501	304	180	171
Max	1447	83,493	7.0	28,597	632	2637	477	644	4	24	1	69	50,817	367	236	220

2.2. OLI Modeling

Water quality for each of the 83 wells/CTBs was input into OLI (OLI Systems Inc., Parsippany, NJ, USA), and the first step in modeling was to reconcile the cation–anion balance. Imbalances in cations and anions were adjusted by the addition of sodium and chloride ions, respectively, to ensure an electrically neutral solution. Following reconciliation, a vapor survey was performed at increments of 1% evaporation increments (by mole%) at a pressure of 1 Atm and a starting temperature of 25 °C. In the output file, the first point of NaCl precipitation was identified, and the distillate recovered and the total solid waste produced was noted at the evaporation point immediately preceding NaCl precipitation. Total solid waste generated (lb/d) was then calculated by multiplying the unit waste produced (in lb/bbl) by the flow rate for the individual well/CTB (bbl/d).

An example of the MLD approach for a hypothetical PW is shown in Figure 1, where it can be seen that most of the solid waste produced during desalination is comprised of highly soluble NaCl. If desalination were to be stopped just before the onset of NaCl precipitation, then solid waste generation can be minimized. In this example, NaCl precipitation started at 69% distillate recovery, and therefore, potential water recovery for this hypothetical PW was assumed to be 68% and the total mass of precipitated solids at 68% distillate recovery was then used to estimate solid waste generation.

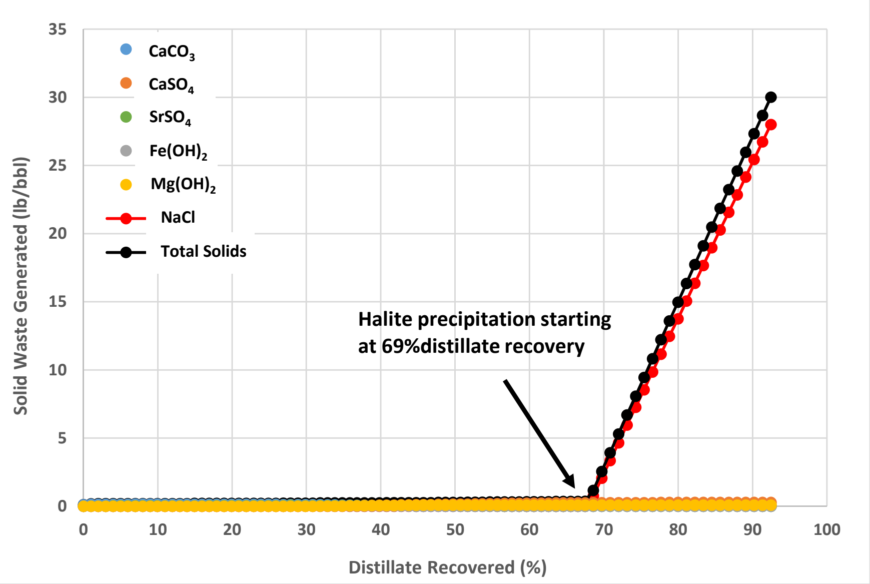

Figure 1. Solids production as a function of distillate recovered during desalination of PW.

As more distillate or clean water is recovered from PW, TDS in the remaining PW (or brine) continues to increase eventually reaching the point of NaCl saturation. The focus of this paper is to understand the chemical composition of the remaining PW with the objective of predicting the point of halite saturation. The chemical composition of the remaining brine is a function of the amount of clean water abstracted or recovered from the original PW and does not depend on the technology employed for desalination. In other words, the analysis and conclusions presented in this paper are independent of the technology employed for desalination.

3. Results and Discussion

3.1. Distillate Recovery

Simulated distillate recovery using an MLD approach (terminating desalination prior to NaCl precipitation) as a function of PW TDS is shown in Figure 2. As expected, the amount of distillate recovered is higher for PWs with lower TDS. Considering all 83 wells with an average TDS of 209,000 mg/L, distillate recovery averaged approximately 41%

(range of 11 to 88%). A linear correlation between percent distillate recovered and PW TDS was also developed as shown in Figure 2. Such a simple correlation can enable a non-expert to rapidly screen PW qualities and estimate potential for distillate recovery without the need for water chemistry/modelling expertise. A similarly strong correlation was found between distillate recovery and chloride concentration (see Figure 3). The interrelationship between TDS/chloride and NaCl precipitation is not entirely unexpected given that chloride is the predominant ion in PW, constituting approximately 60% of the total ions in solution.

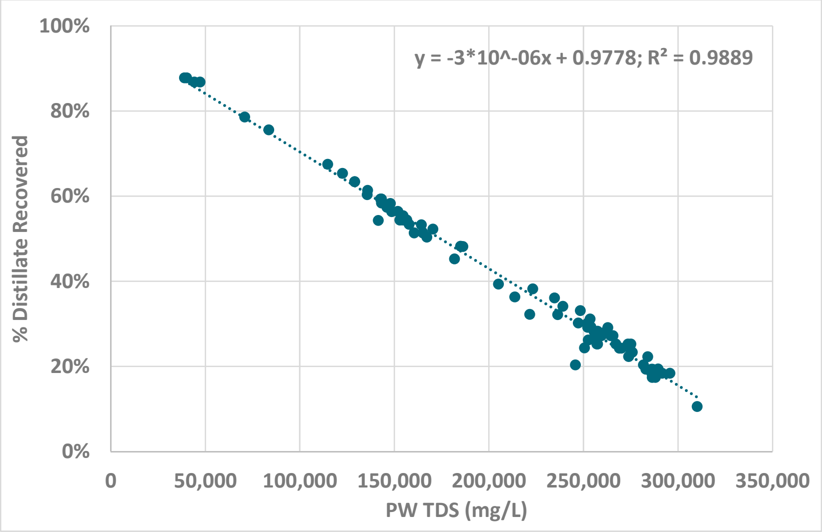

Figure 2. Modelled distillate recovery as a function of PW TDS using an MLD approach.

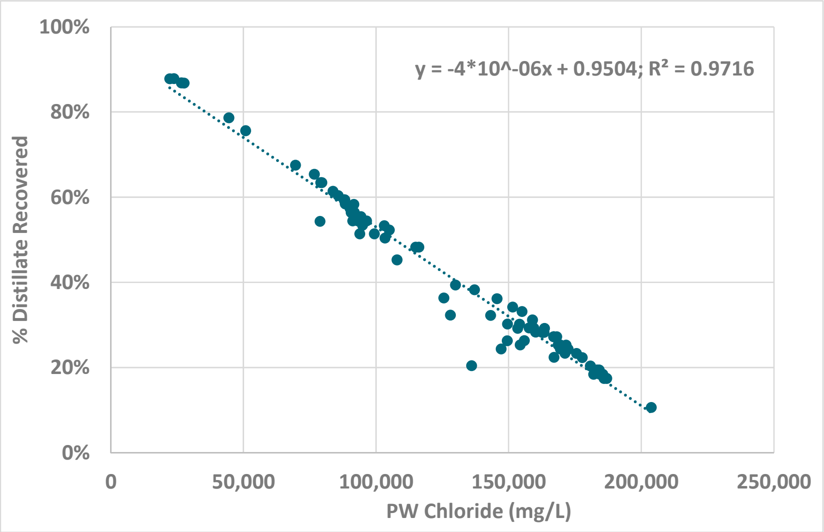

Figure 3. Modelled distillate recovery as a function of PW Chloride using an MLD approach.

3.2. Solid Waste Generation

Solid waste generated using the MLD approach is shown in Figure 4. Waste generation averaged approximately 0.15 lbs/bbl PW desalinated (range of 0.002 to 0.68 lbs/bbl). Unlike distillate recovery, correlation between waste generated (up to the point of NaCl precipitation) and TDS was poor; however, waste generated seemed to generally trend lower with increasing TDS. Up to the point of NaCl precipitation, the waste generated is comprised of sparingly soluble solids such as calcite, barite and celestite. Management of such sparingly soluble waste is relatively straightforward and typically comprises settling/filtering the solids generated, followed by thickening and dewatering steps to produce a high solids content cake, which can then be disposed in a conventional (non-hazardous) landfill.

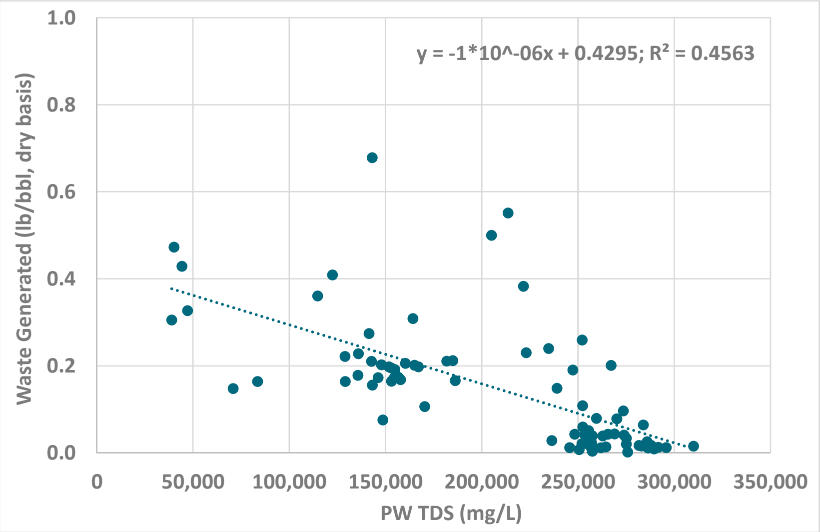

Figure 4. Estimated solid waste generated (lb/bbl) via MLD as a function of PW TDS.

3.3. *Selective MLD—Focussing Desalination Efforts on High Flow Rate and Low TDS PWs*

A further refinement of the MLD approach for PW desalination described in this paper is to consider limiting desalination treatment to a subset of high flow rate wells only or an even smaller subset of high flow rate wells with lower TDS. The objective of evaluating such a selective MLD approach is to determine the feasibility of recovering substantial distillate for beneficial use while minimizing the volume of PW that needs to be treated/desalinated, and therefore, minimize the cost of desalination. For the purpose of this analysis, the flow rate cut-off was arbitrarily set at 450 bbl/d, which decreased the number of wells/CTBs from 83 to 36 while still accounting for 89% of the total flow. Similarly, TDS limits was arbitrarily set at <250,000 mg/L, <180,000 mg/L and <150,000 mg/L, which reduced the number of candidate wells/CTBs to 17, 11 and 8, respectively. Water recovery and waste generation using such a selective MLD approach are shown in Table 2.

Table 2. Utilizing a selective MLD approach to optimize distillate recovery.

MLD Desalination Scenario	**# of Wells**	**Total Flow Rate**	**Avg. TDS**	**Distillate Recovered**	**Total Solid Waste**
		bbl/d	**mg/L**	**bbl/d (%)**	**lb/d**
No flow rate or TDS limit	83	66,556	208,867 min: 39,000 max: 310,000	27,003 (41%)	12,216
Subset of high flow rate wells; no TDS limit	36	58,916	213,520 min: 39,000 max: 310,000	23,172 (39%)	10,823
Subset of high flow rate wells; TDS < 250,000 mg/L	17	34,764	148,594 min: 39,000 max: 248,000	19,903 (57%)	10,126
Subset of high flow rate wells; TDS < 180,000 mg/L	11	27,213	103,662 min: 39,000 max: 170,000	19,076 (70%)	9029
Subset of high flow rate wells; TDS < 150,000 mg/L	8	25,317	82,580 min: 39,000 max: 143,000	19,303 (76%)	8729

Restricting desalination to wells with a flow rate greater than 450 bbl/d reduced PW volume processed/desalinated by 11% (from 66,556 to 58,916 bbl/d) while decreasing distillate recovered by 14% (from 27,003 to 23,172 bbl/d). Therefore, selectively desalinating higher flow rate wells with an MLD approach did not result in significant efficiency in distillate recovery because the higher flow rate wells had nearly the same average TDS as that of the larger dataset. However, using a TDS cut-off for desalination did result in greater efficiency in distillate recovery. For example, restricting desalination of the high flow rate wells to those with TDS less than 150,000 mg/L reduced the volume of PW requiring desalination by 62% (from 66,556 to 25,317 bbl/d) but with a much smaller reduction 29% reduction in distillate recovered (from 27,003 to 19,303 bbl/d). Waste generation on a normalized basis, however, was much higher; 0.18 lb/bbl vs. 0.34 lb/bbl for all wells vs. those with a cut-off of 150,000 mg/L TDS, respectively. However, as will be shown later, overall waste generation is still much lower than that produced by a ZLD process.

In summary, selective application of an MLD approach was predicted to yield substantial volumes of distillate for beneficial use while greatly reducing the volume of PW that would have to be processed via desalination as well as greatly minimizing waste generation.

3.4. Comparison of Selective MLD and Traditional Desalination Approaches

To illustrate the benefits of an MLD vs. ZLD approach, three scenarios were evaluated as described below, and the results are shown in Table 3.

Selective MLD—high flow rate and low TDS PWs:

1. Only high flow rate wells with average TDS $\leq$ 100,000 mg/L will be selectively targeted for desalination; treatment will be at the well-pad level.
2. An MLD approach will be used by terminating desalination just before NaCl precipitation; small quantities of largely insoluble waste will be generated.
3. Residual brine will be injected in SWD wells.

Selective ZLD (Evaporation and Crystallization)—high flow rate and low TDS PWs:

1. Only high flow rate wells with average TDS $\leq$ 100,000 mg/L will be selectively targeted for desalination; treatment will be at the well-pad level.
2. The desalination process will be operated beyond the point of halite precipitation up to practical limits of operation.
3. Any residual brine will be evaporated to dry solids (zero liquid waste); all of the TDS in PW will precipitate out of solution; solid waste will comprise predominantly soluble salts.

Large-Scale ZLD (Crystallization)—no restriction on flow rate or TDS:

1. PW will be desalinated regardless of TDS or flow rates to obtain maximum distillate volumes; treatment will be at CTBs.
2. The desalination process will be operated beyond the point of halite precipitation up to practical limits of operation.
3. Any residual brine will be evaporated to dry solids (zero liquid waste); all of the TDS in PW will precipitate out of solution; solid waste will comprise predominantly soluble salts.

As can be seen from the above analysis, the use of a selective MLD approach to PW desalination is far more advantageous than either ZLD approaches. Using an MLD approach does result in lower recovery of distillate and still leaves a liquid waste that requires disposal. However, this liquid waste constitutes a fraction of the original PW volume, and can be transported using existing infrastructure to SWD wells for disposal. Further, the liquid waste/saturated brine waste may also offer potential opportunities for recovery of valuable elements such as lithium, bromine and other elements of commercial value prior to disposal [3].

Table 3. Comparison of Selective MLD and Selective and Large-Scale ZLD approaches for PW management.

Parameter	Units	Selective MLD	Selective ZLD	Large-Scale ZLD
Attributes		• Focus on low TDS/high flow rate PW • MLD; stop before NaCl precipitation • Liquid waste to disposal (SWD) • Implemented on a well-pad level	• Focus on low TDS/high flow rate PWs • Evaporator/Crystallizer • Liquid waste evaporated to dryness • Implemented on a well-pad level	• No restriction on flow rate or TDS • Crystallizer • Liquid waste evaporated to dryness • Implemented at CTBs
PW Flow Rate	bbl/d	100,000	100,000	100,000
Average TDS	mg/L	<100,000	<100,000	210,000 (average of 83 well dataset)
Distillate Recovered	%	70 (this study)	90 (estimated from Ghurye, et al. [3])	80 (estimated from Ghurye, et al. [3])
Liquid Waste Generated	bbl/d	30,000 (injected into SWD wells)	0 (zero liquid waste)	0 (zero liquid waste)
Solid Waste Generated				
Sparingly Soluble Waste	tons/d	15	15	15
NaCl	tons/d	0	1067	2242
Mixed Waste (liquid waste evaporated to dryness)	tons/d	0	536	1125
Solid Waste Characteristics		• Sparingly soluble • Disposal in conventional landfills	• Highly soluble waste • May need hazardous waste disposal in specialized landfills	• Highly soluble waste • May need hazardous waste disposal in specialized landfills
Solid Waste Transportation (@ 21 tons/truck)	trucks/d	<1	77	161

A ZLD approach, on the other hand produces no liquid waste and recovers 15–30% more distillate than MLD. However, this incremental distillate recovery is offset by the large quantity of highly soluble, and therefore, difficult-to-manage solid waste. Based on the quantity of solid waste generated, ZLD will also incur higher transportation costs than MLD. Further, there are no examples of solid landfills that accept large quantities of highly soluble waste. If implemented, the use of ZLD will therefore require research into designing specialized landfills capable of sustainably sequestering such highly soluble wastes.

3.5. Considerations for the Application of a Selective MLD Approach to Desalination of Unconventional PWs

As can be seen from the discussion above, the two main parameters required to implement a selective MLD approach are flow rate and TDS. While flow rate data is generally automated and readily available, obtaining the TDS of PW requires a sample to be sent to a laboratory for analysis. To enable rapid decision making, the use of conductivity as a surrogate for TDS should be investigated. For example, the conductivity of PWs from a representative number of wells can be measured in the field and a split sample can be sent off-site for TDS analysis. A correlation can then be developed relating conductivity to TDS. Rapidly deployable (mobile) and modular desalination technologies will have to be identified and their performance will have validated via bench and/or pilot studies. The accuracy of OLI modeling and waste generation estimates should also be verified during technology validation studies.

3.6. Considerations for Beneficial Use of Desalinated Water within and Outside the O&G Industry

A hierarchy of beneficial uses should be developed based on use-specific risk and exposure to environmental receptors based on initial distillate quality. For example, although low-TDS/fresh water quality is not required, use for fracturing operations within the O&G industry could pose the lowest risk as the distillate (and any unidentified constituents contained in it) will not be introduced into the environment. Next, other uses within O&G industry for purposes such as dust control (in the vicinity of well pads) and cooling water should be explored, and potential risks and distillate treatment options should be identified to mitigate any identified risks. Thus, a combination of uses of desalinated PW within the O&G industry can substantially or completely offset industry’s fresh and brackish water withdrawals, leaving these natural resources for use by local consumers.

Once this internal demand is substantially or fully satisfied, beneficial uses outside the O&G industry can be contemplated. For such beneficial use, desalinated PW should be considered a new source water that requires thorough investigation to enable science-based regulations governing its use. Given that the composition of PW is both spatially and temporally variable, the quality of desalinated PW may be expected to vary as well. Therefore, both PW and distillate quality should be adequately characterized and use-based environmental receptors should be identified to develop a robust toxicology and risk framework.

Finally, if there is no proximate demand for desalinated PW and conveyance to the location of demand is not economically feasible, releasing the distillate as steam into the atmosphere can be explored. The presence and potential environmental ramifications of distillate constituents in such emissions will have to be addressed prior to release. In such a scenario, even if distillate is not captured for beneficial use, a substantial reduction in the volume of PW can be achieved, which can be advantageous in locations where disposal of PW via SWD may face constraints.

4. Conclusions

The findings of this study demonstrated the advantages of using a selective MLD desalination approach for management of unconventional PWs. A comparison between selective MLD, with a focus on desalination of high flow rate and lower TDS wells, was determined to be a superior option to selective and large-scale ZLD. Sufficient distillate can be obtained from a selective MLD approach to offset the O&G industry’s withdrawals of fresh and brackish groundwater in NM. By selective application of MLD, the waste generated from desalination of PW can be minimized, thus addressing one of the major challenges associated with desalination of unconventional O&G PWs.

Further, a simple correlation between PW TDS and distillate recovery can be used to rapidly evaluate the feasibility of a selective MLD approach as an alternative option for management of unconventional PWs. Although this study focused on PW in NM, the selective MLD approach used in this study may be applicable to other unconventional PWs as well.

A hierarchy of beneficial uses should be developed and lower risk options identified for initial use of desalinated PW. As research progresses and adequate characterization of the composition of PW and distillate is available and a robust risk assessment framework is developed, other beneficial uses can be studied to ensure environmentally responsible use of desalinated PW.

5. Recommendations for Future Research

As seen from the above discussion, the use of an MLD approach for desalination of PW is a promising option that can complement the baseline options currently used by the O&G industry to manage unconventional PWs. However, significant research is needed to ascertain the feasibility of, and operationalize, an MLD approach to desalination of unconventional PWs. Based on the results of this study, the following recommendations are offered for future research.

1. The results obtained from OLI modeling of PW should be verified at the bench and/or pilot scale to confirm modeled distillate recovery and solid waste generated as a function of PW TDS. Further, to implement a selective MLD approach will require real-time data on PW flow rates and TDS. An accurate correlation between TDS and conductivity will have to be developed to enable rapid selection of potential wells/well pads for implementation of an MLD approach.
2. Mobile and rapidly deployable, modular desalination technologies will have to be identified/developed and validated. Technologies that require little to no pretreatment prior to desalination can provide operations flexibility and reduce costs. Further, emerging technologies such as MD, which have the potential to use waste and/or renewable sources of energy, should also be explored to enable cost-effective desalination of unconventional PWs.
3. To enable beneficial use outside the O&G industry, the composition of desalinated PW will have to be adequately characterized to ensure that potential environmental and human health impacts, if any, are mitigated to acceptable toxicology and/or regulatory end-points.

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