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Treatability of a Highly-Impaired, Saline Surface Water for Potential Urban Water Use

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Abstract: As freshwater sources of drinking water become limited, cities and urban areas must consider higher-salinity waters as potential sources of drinking water. The Salton Sea in the Imperial Valley of California has a very high salinity (43 ppt), total dissolved solids (70,000 mg/L), and color (1440 CU). Future wetlands and habitat restoration will have significant ecological benefits, but salinity levels will remain elevated. High salinity eutrophic waters, such as the Salton Sea, are difficult to treat, yet more desirable sources of drinking water are limited. The treatability of Salton Sea water for potential urban water use was evaluated here. Coagulation-sedimentation using aluminum chlorohydrate, ferric chloride, and alum proved to be relatively ineffective for lowering turbidity, with no clear optimum dose for any of the coagulants tested. Alum was most effective for color removal (28 percent) at a dose of 40 mg/L. Turbidity was removed effectively with 0.45 μm and 0.1 μm microfiltration. Bench tests of Salton Sea water using sea water reverse osmosis (SWRO) achieved initial contaminant rejections of 99 percent salinity, 97.7 percent conductivity, 98.6 percent total dissolved solids, 98.7 percent chloride, 65 percent sulfate, and 99.3 percent turbidity.

Keywords: coagulation; desalination; Salton Sea; sea water reverse osmosis; treatability

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1. Introduction

Many inland bodies of water suffer from rising salinity which can harm biota and impair or prevent beneficial water use [1]. Salinization occurs when salts and minerals in soil are mobilized from clearing natural vegetation [2], when fresh water is diverted for irrigation [3], there are ongoing or reoccurring drought conditions [4], or as a result of municipal wastewater discharges [5]. As freshwater sources of drinking water become limited, cities and urban areas must consider higher-salinity waters as potential sources of drinking water.

The Salton Sea is a large, shallow saline lake in an arid desert area of Southern California. It was formed by an accidental diversion of the Colorado River into the Salton Sink between 1905 and 1907. The lake is the largest and lowest inland water body in California with a total surface area of 980 km^2, a maximum depth of approximately 15 m, and approximately 70 m below mean sea level. It is a closed-basin lake with no outlet, sustained by irrigation return flows and municipal wastewater discharges. Initially a freshwater lake, a high nutrient loading from agricultural runoff, continuous municipal wastewater treatment effluent discharges, and no natural outflow has resulted in a steady decline in water quality over many decades [6]. Diversion of agricultural water to municipal use beginning 1 January 2018 further threatens water quality, but is also expected to result in further shrinking the size of the Salton Sea [7].

The Salton Sea has been the subject of significant research, and its water quality deterioration is well characterized [8–11]. Despite being a hypereutrophic, hypersaline water body, the Salton Sea provides a significant ecological function, and is a vital habitat for migrating birds. Development and implementation of plans to remediate the Salton Sea ecosystem has been an ongoing challenge for the California Department. of Water Resources [7] and the approximately 650,000 people living with the air basin impacted by dust from the sea [12]. Indeed, the economic cost of doing nothing to remediate the Salton Sea far outweigh the cost of remediation proposals [12]. Various alternatives to remediate the ecosystem have been put forth by stakeholders and evaluated by the U.S. Bureau of Reclamation [13]. Alternatives generally involve wetlands and habitat restoration using shallow water impoundment dikes. Construction of a desalination reverse osmosis (RO) plant has also been proposed to produce freshwater for potential urban or groundwater recharge uses [14]. Importation of water from Mexico has also been proposed as a way to maintain sea water at a sustainable level [15]. In November 2017, the California Water Resources Control Board accepted a 10-year plan to construct 29,800 acres of ponds, wetlands, and dust suppression projects on the exposed lake bed [16]. Future habitat restoration and dust suppression will have significant benefits for ecological restoration, but salinity concentrations will still be too high for the Salton Sea to serve as a potential urban water supply without desalination.

In practice, industrial water desalination is most often accomplished using one of four processes: multi-stage flash distillation, multiple effect distillation, vapor-compression evaporation and RO [17]. These technologies are primarily limited by high energy costs, a large concentrate (brine) waste discharge, and the need to pump water from the sea. RO typically consumes less than 10 to 50 percent of the total equivalent energy required by other desalination technologies [18]. Further, RO is commonly used for drinking water treatment in the United States when desalination is necessary, with application of other desalination processes generally limited to industrial water treatment. Even so, multi-effect distillation with a vertical tube evaporator is being tested by the U.S. Bureau of Reclamation for geothermal distillation of Salton Sea water [19]. On the southeast bank of the Salton Sea is a seismically active geothermal field under consideration for future geothermal energy development [20–22].

This present study explores the treatability of Salton Sea water for potential urban water use when other options are limited or non-existent. The quality and treatability of Salton Sea water is compared to that of Pacific Ocean water using jar tests and RO desalination. RO was evaluated here because of its familiarity within the drinking water industry and low energy requirements compared to other desalination processes. Because of its high salinity, Salton Sea water is expected to cause severe chemical fouling of RO membranes on a long-term basis, unless pretreatment is provided. The initial tests of RO technology conducted here are intended primarily to assess contaminant rejection. Should contaminant rejection using RO with minimal pretreatment be effective, future studies could be considered to optimize pretreatment and evaluate long-term RO performance.

2. Materials and Methods

The effectiveness of RO treatment of Salton Sea water and Pacific Ocean water was evaluated at the bench scale. Pretreatment of Salton Sea water using cartridge filtration and coagulation was also assessed.

In August 2017, multiple 19 L containers of water were taken from the Salton Sea north shore and the Pacific Ocean at Cabrillo Park, California, and transported to the environmental engineering laboratory at California Baptist University (CBU). Raw Salton Sea water (SSW) and Pacific Ocean water (POW) samples were tested for the constituents listed in Table 1, which summarizes the sampling plan followed in this study. A process flow diagram and sampling locations are provided in Figure 1.

2.1. Cartridge Filtration

After collection, SSW and POW samples were filtered through a 30 µm spiral-wound cartridge filter prior to further testing.

2.2. Coagulation

Jar tests were performed on Salton Sea water to assess the effectiveness of coagulation for color removal. Aluminum chlorohydrate (ACH), ferric chloride (ferric), and aluminum sulfate (alum) were evaluated.

Table 1. Sampling and Analysis Plan [1].

Constituent	Salton Sea Water				Pacific Ocean Water			
	Raw	Filt	Perm	Reject	Raw	Filt	Perm	Reject
Alkalinity	X	X	X	X	X	X	X	X
Aeromonas	X	-	-	-	X	-	-	-
Ca^{2+} Hardness	X	X	X	X	X	X	X	X
Chloride	X	-	X	X	X	-	X	X
Color	X	-	X	X	X	-	X	X
Conductivity	X	-	X	X	X	-	X	X
E. coli	X	X	X	X	X	X	X	X
HPC [1]	X	X	X	X	X	X	X	X
pH	X	-	X	X	X	-	X	X
Salinity	X	-	X	X	X	-	X	X
Sulfate	X	-	X	X	X	-	X	X
Suspended Solids	X	-	X	X	X	-	X	X
Total Coliform	X	-	-	-	X	-	-	-
Total Hardness	X	-	X	X	X	-	X	X
Total Solids	X	-	X	X	X	-	X	X
Turbidity	X	X	X	X	X	X	X	X
UV254	X	-	X	X	X	-	X	X

Note: [1] HPC = heterotrophic plate count; Filt = 30 µm filtered; Perm = RO permeate; Reject = RO concentrate; X = analysis was performed; - = analysis was not performed

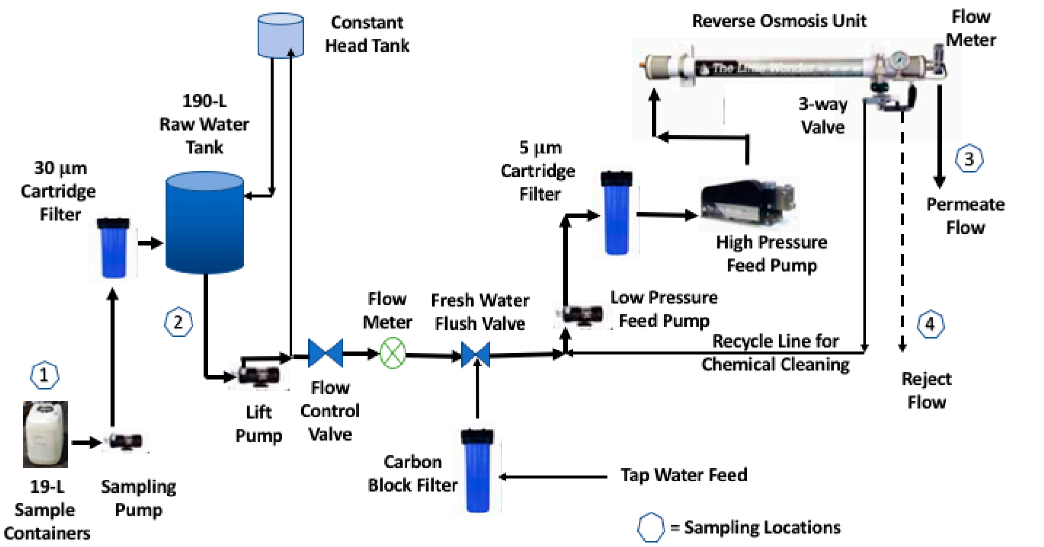

Figure 1. Process flow diagram and sampling locations.

2.2.1. Jar Testing

A series of jar tests were conducted following ASTM D 2035-08, Standard Practice for Coagulation-Flocculation Jar Test of Water [23]. Stock solutions were prepared for each coagulant at a concentration of 10,000 mg/L. A jar test was conducted for each coagulant at doses of 0, 10, 20, 30, 40, and 50 mg/L. Coagulants were added with rapid mixing for 2 min, slow mixing for 30 min (tapered at

10 min intervals), and settling for 45 min. Aliquots were taken from each jar for analysis of turbidity, pH, alkalinity, and color.

The effectiveness of filtration pretreatment was assessed by filtering settled jar test samples through filters with consecutively smaller nominal pore sizes. Sand filtration was simulated by passing settled water through Whatman 40 (8 µm) paper filters (Fisher Scientific, Waltham, MA, USA). Microfiltration was simulated by passing settled water through a 0.45 µm membrane filter followed by a 0.1 µm membrane filter using vacuum filtration.

2.2.2. Bench RO Treatment

The effectiveness of RO treatment was assessed at the bench scale by passing approximately 75 L of filtered Salton Sea water through a sea water reverse osmosis (SWRO) unit described in Table 2. Samples of feed water, permeate and concentrate were collected and analyzed according to the sampling plan presented in Table 1. For comparison, an identical SWRO treatment test was performed on Pacific Ocean water.

Table 2. Bench Scale Sea Water Reverse Osmosis (SWRO) System Specifications [24].

Item	Design Criteria
Manufacturer	Parker Hannifin Corp./Village Marine
Model No.	LWM-200
No. Modules	1
Module Diameter	4-inch
Module Length	40-inch
No. Elements	1 (Aqua Pro® Sea Water RO Membrane (Parker Hannifin Corp., Gardena, California, CA, USA)
Membrane Type	Thin-Film Composite
Membrane Surface Area	1 m^2 (estimated)
Pre-filter	Pentek® 5 µm polypropylene (Pentair) (Parker Hannifin Corp., Gardena, California, CA, USA)
High-Pressure Pump	708 Titan Series (Aqua Pro Pumps, Gardena, California, CA, USA)
Max. Operating Pressure	1000 psi
Max. Operating Temp.	45 °C
Design Flux	30 Lmh (estimated)
Design Product Flow	0.8 m^3/day (210 gpd)
Max. Feed Turbidity	NTU [1]
Free Chlorine Tolerance	0 ppm (5 µm carbon block filter provided)
Max. Feed SDI [1]	SDI 5
Typical Salt Rejection	99.0 percent
pH range	4 to 11 (2.5 to 11 during short-term cleaning)

Note: [1] Silt Density Index.

Feed water was pumped through the SWRO system at 20 L/h for 60 min at 58 to 66 bar transmembrane pressure (TMP). Samples were taken for analysis of the SWRO feed water, permeate, and reject stream. Initial contaminant rejection was assessed by taking composite samples over the 60 min operating period. TMP, permeate flow, and reject water flow were monitored during the test. The volume of water treated (20 L) and duration of testing (60 min) was limited, due to having to transport raw water to the laboratory for testing. Given the short-term of testing, normalization of test results was not necessary.

3. Analytical Methods

All analyses were performed at the CBU environmental engineering laboratory. The analytes and analytical methods used are presented in Table 3. *Standard Methods* [25], U.S. Environmental Protection Agency (EPA) methods [26], or their equivalent as developed by Hach [27] and Micrology Laboratories [28], were used. Quality assurance (AQ) and quality control (QC) measures were followed along standard laboratory practices for instrument calibration according to the manufacturer's instructions. Filtration through a 0.45 µm membrane filter was performed prior to ultraviolet absorbance (UVA) (Hach DR5000 UV VIS, Loveland, Colorado, CO, USA) and 254 nm (UV254) (Hach DR5000 UV VIS, Loveland, Colorado, CO, USA). All experiments and analyses were performed at laboratory temperature (22 °C).

Table 3. Analytical Methods.

Analyte	Technique	Analytical Method
Alkalinity	Titrimetric, pH 4.5	EPA Method 310.1
Aeromonas	Easygel ECA Check [1]	*Standard Methods* 9223 *
Ca^{2+} Hardness	Titrimetric, EDTA	Hach Method 8204
Chloride	Mercuric Nitrate Titration	Hach Method 8206
Color	Platinum-Cobalt	*Standard Methods* 2120
Conductivity	Conductivity Cell	*Standard Methods* 2510
HPC	Easygel Total Count T-salt [1]	*Standard Methods* 9215B *
pH	Electrometric	EPA Method 150.1
Salinity	Mercuric Nitrate Titration	Hach Method 10073
Sulfate	Turbidimetric	Hach Method 10227
Suspended Solids	Gravimetric	EPA Method 160.1
Total Coliform	Easygel ECA Check [1]	*Standard Methods* 9223 *
Total Hardness	Titrimetric, EDTA	Hach Method 8213
Total Solids	Gravimetric	EPA Method 160.1
Turbidity	Nephelometer	EPA Method 180.1
UV254	UVA at 254 nm	EPA Method 415.3

Note: [1] Micrology Laboratory, Goshen, Indiana, IN, USA; * Modified pour plate method developed by the manufacturer (Micrology Laboratory, Goshen, Indiana, IN, USA).

4. Results and Discussion

Results of water quality testing, cartridge filtration, jar testing, and SWRO bench testing are presented below. Analytical results for all water quality tests are presented in Tables 4 and 5 for SSW and POW, respectively.

Table 4. Salton Sea Water Analytical Results [1].

Constituent	Units	Salton Sea Water			
		Raw	Feed	Permeate	Reject
Alkalinity	mg/L as $CaCO_3$	276	268	12	288
Aeromonas	CFU/mL	33	-	-	-
Ca^{2+} Hardness	mg/L as $CaCO_3$	2200	2050	14	2200
Chloride	mg Cl^-/L	38,000	25,400	500	27,700
Color	CU	1440	1300	58	127
Conductivity	mS/m	71.9	71.3	1.65	77.0
HPC [1]	CFU/mL	66	32	14	122
pH	units	8.1	-	7.9	8.06
Salinity	ppt	43	39	0.4	46.7
Sulfate	mg SO_4^{2-}/L	20,800	17,700	ND	19,500
Suspended Solids	mg/L	44	-	ND	162
Total Coliform	CFU/mL	37	-	-	-
Total Hardness	mg/L as $CaCO_3$	17,500	9300	38	10,900
Total Solids	mg/L	70,200	-	913	77,136
Turbidity	NTU	25.1	11.6	0.16	10.6
UV254	cm^{-1}	0.696	0.69	0.013	0.815

Note: [1] HPC = heterotrophic plate count; Filtered = 30 µm filtered; Permeate = RO permeate; Reject = RO concentrate; ND = none detected; CFU = colony forming units.

Table 5. Pacific Ocean Water Analytical Results [1].

Constituent	Units	Pacific Ocean Water			
		Raw	Feed	Permeate	Reject
Alkalinity	mg/L as $CaCO_3$	126	124	10	168
Aeromonas	CFU/mL	None	-	-	-
Ca^{2+} Hardness	mg/L as $CaCO_3$	900	875	4	1250
Chloride	mg Cl^-/L	18,800	18,300	380	24,000
Color	CU	ND	ND	ND	1
Conductivity	mS	48	47	0.82	60
HPC [1]	CFU/mL	2047	243	1	3470
pH	units	8.0	-	7.5	8.0
Salinity	ppt	30.3	30.6	0.2	39.2
Sulfate	mg SO_4^{2-}/L	262	263	ND	334
Suspended Solids	mg/L	9	-	1	8
Total Coliform	CFU/mL	None	-	-	-
Total Hardness	mg/L as $CaCO_3$	4700	4900	24	8800
Total Solids	mg/L	39,443	-	410	47,121
Turbidity	NTU	0.491	0.5	0.229	1.85
UV254	cm^{-1}	0.017	0.016	0.015	0.13

Note: [1] HPC = heterotrophic plate count; Feed = 30 µm filtered; Permeate = RO permeate; Reject = RO concentrate; ND = none detected.

4.1. Cartridge Filtration

Salton Sea water and Pacific Ocean water were filtered through a 30 µm cartridge filter prior to performing SWRO bench tests. Turbidity removal of 54 percent was achieved for SSW. No significant removal of turbidity was achieved using a cartridge filter for POW because of the low raw water turbidity.

4.2. Water Quality Test Results

Consistent with prior studies, the Salton Sea water quality was found to be highly saline (43 ppt). The SSW chloride and total dissolved solids (= total solids − suspended solids) concentrations were 38,000 mg Cl^-/L and 70,000 mg/L, respectively. In contrast, POW chloride and total dissolved solids concentrations were 18,800 mg Cl^-/L and 39,434 mg/L, respectively.

4.3. Jar Test Results

The Salton Sea is highly colored. Results of jar testing are presented in Figures 2–7. Coagulation-sedimentation proved to be relatively ineffective for lowering turbidity with no clear optimum dose for any of the coagulants tested (Figures 2–4).

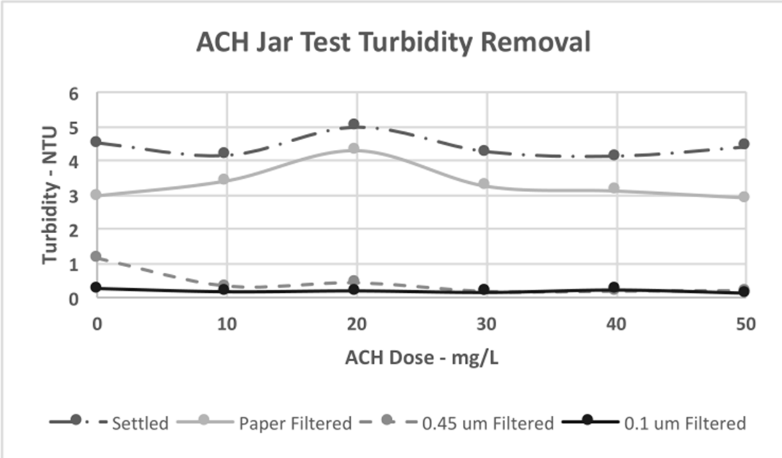

Figure 2. Turbidity after settling versus ACH dose and filtering through 8 µm filter paper, a 0.45 µm membrane filter, and a 0.1 µm membrane filter.

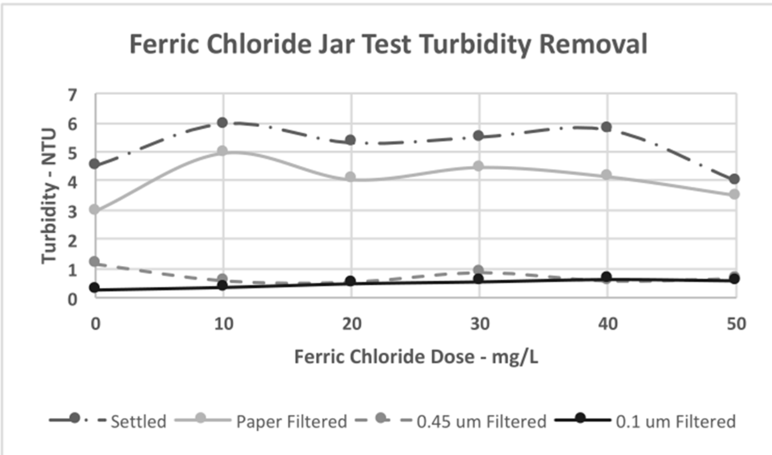

Figure 3. Turbidity after settling versus ferric dose and filtering through 8 µm filter paper, a 0.45 µm membrane filter, and a 0.1 µm membrane filter.

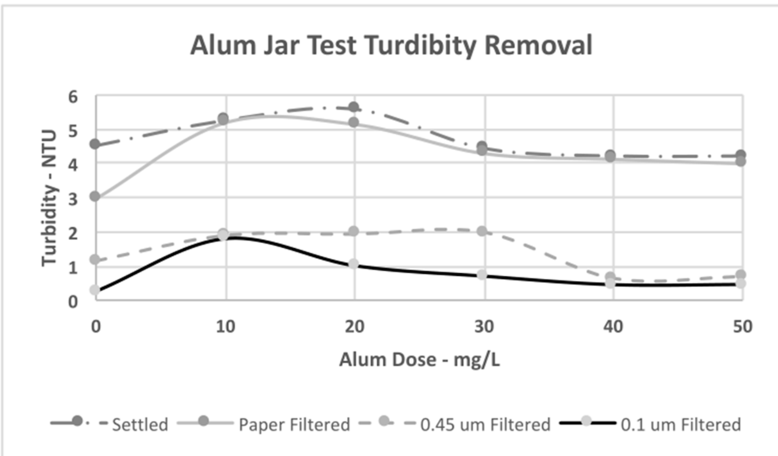

Figure 4. Turbidity after settling versus alum dose and filtering through 8 µm filter paper, a 0.45 µm membrane filter, and a 0.1 µm membrane filter.

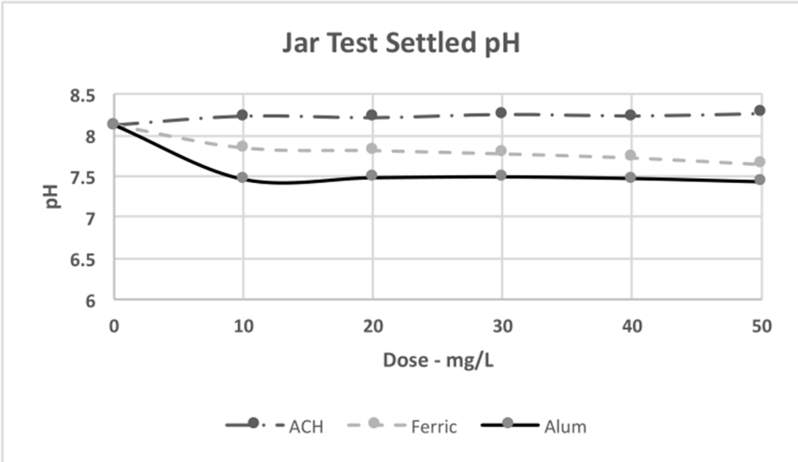

Figure 5. Jar test settled pH versus coagulant dose.

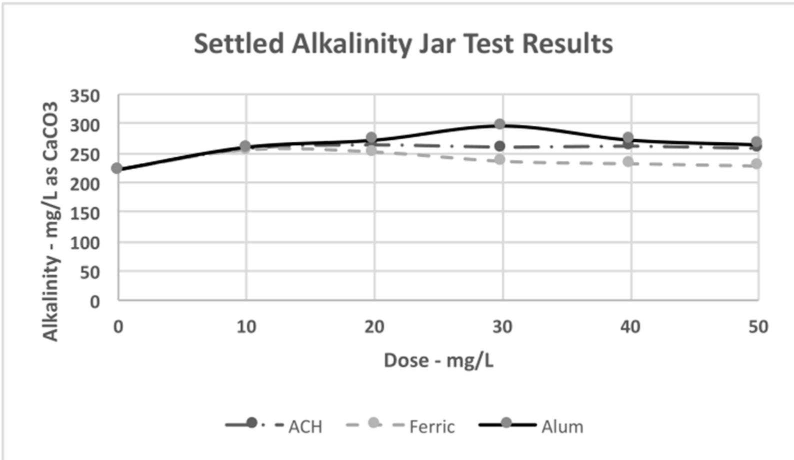

Figure 6. Jar test settled alkalinity versus coagulant dose.

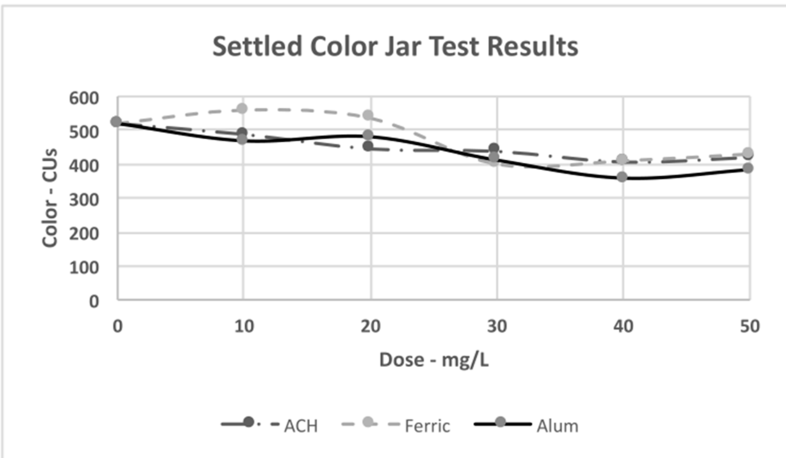

Figure 7. Jar test settled color versus coagulant dose.

ACH generally increased pH (Figure 4) and alkalinity (Figure 5), whereas ferric and alum lowered pH and alkalinity. Alum was most effective for color removal (28 percent) at a dose of 40 mg/L.

4.4. SWRO Treatability Results

The feed flow rate during SWRO testing was 75 L/h. The permeate flow rate was 7.95 L/h and 9.2 L/h during treatment of SSW and POW, respectively. An average recovery of 10.6 percent and 12.2 percent was achieved for SSW and POW, respectively.

SWRO water quality test results for SSW and POW are presented in Tables 4 and 5, respectively. Salinity (Figure 8), conductivity (Figure 9), total dissolved solids (TDS) (Figure 10), chloride (Figure 11), sulfate (Figure 12), and turbidity (Figure 13) were all removed. SWRO contaminant rejection is summarized in Figure 14.

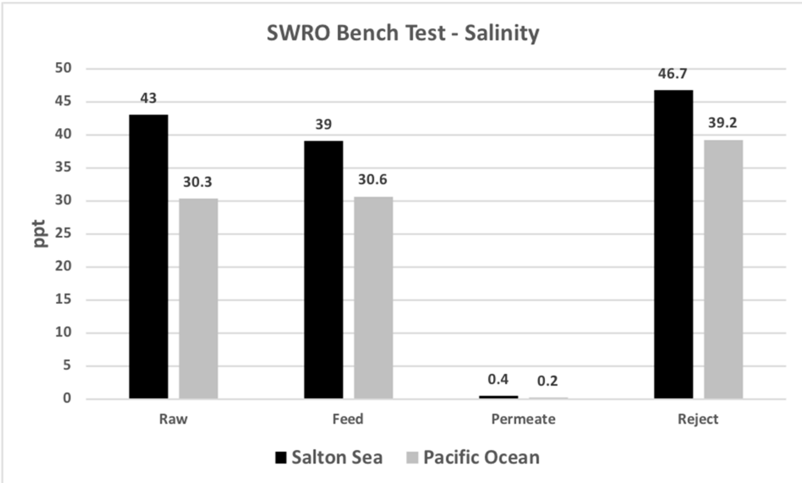

Figure 8. Salinity of raw water, SWRO feed, permeate, and reject flow.

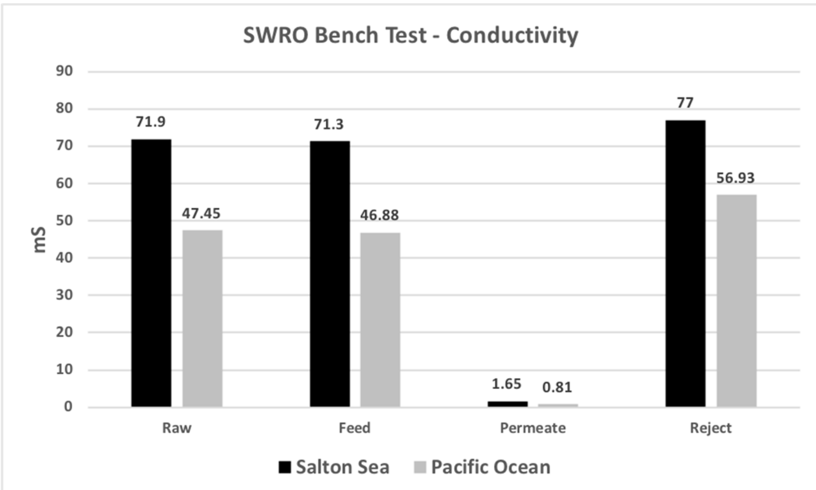

Figure 9. Conductivity of raw water, SWRO feed, permeate, and reject flow.

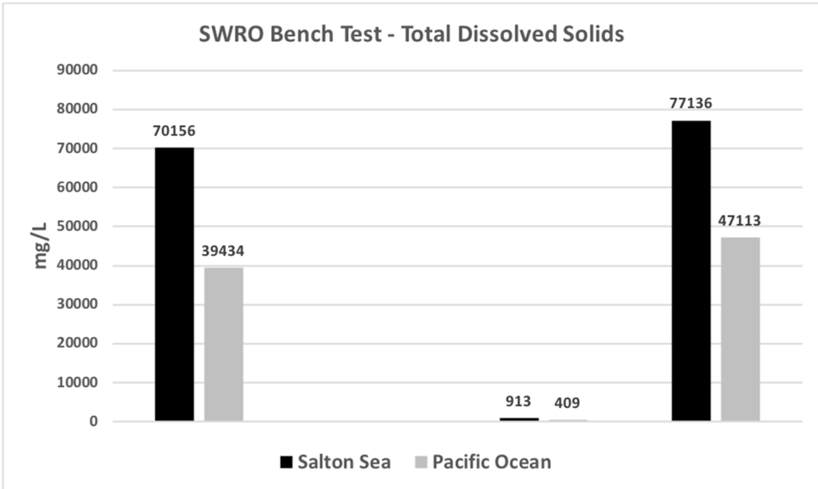

Figure 10. Total dissolved solids (TDS) of raw water, SWRO feed, permeate, and reject flow. TDS = total solids − suspended solids.

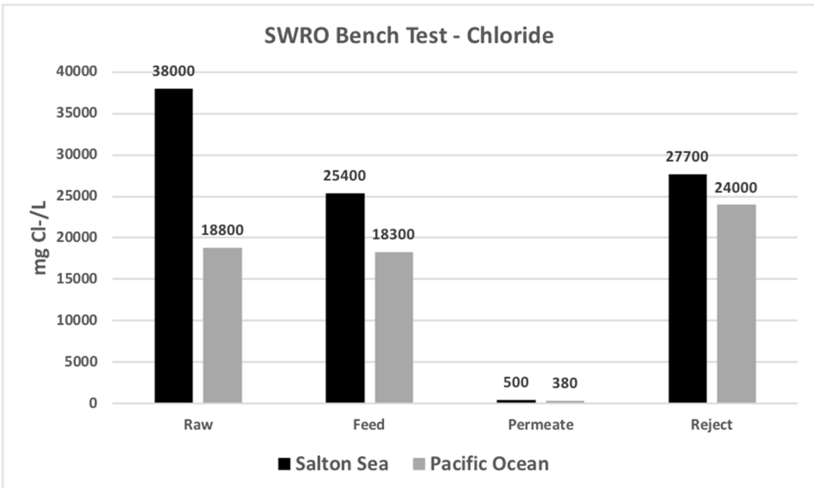

Figure 11. Chloride of raw water, SWRO feed, permeate, and reject flow.

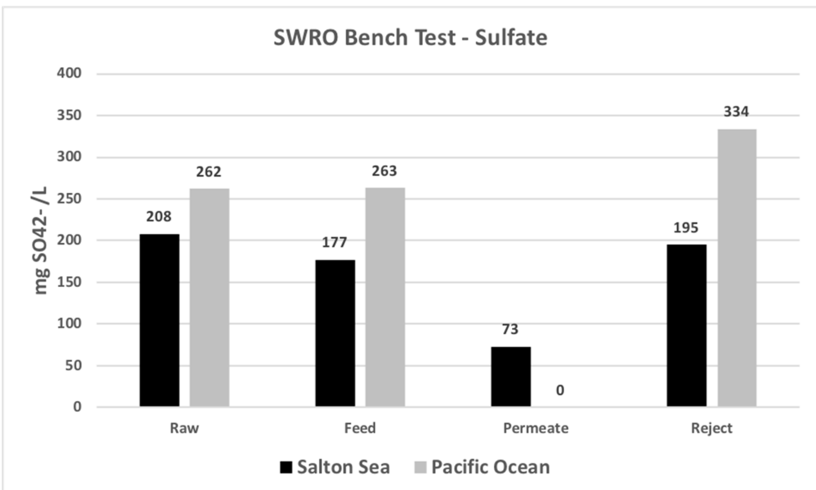

Figure 12. Sulfate of raw water, SWRO feed, permeate, and reject flow.

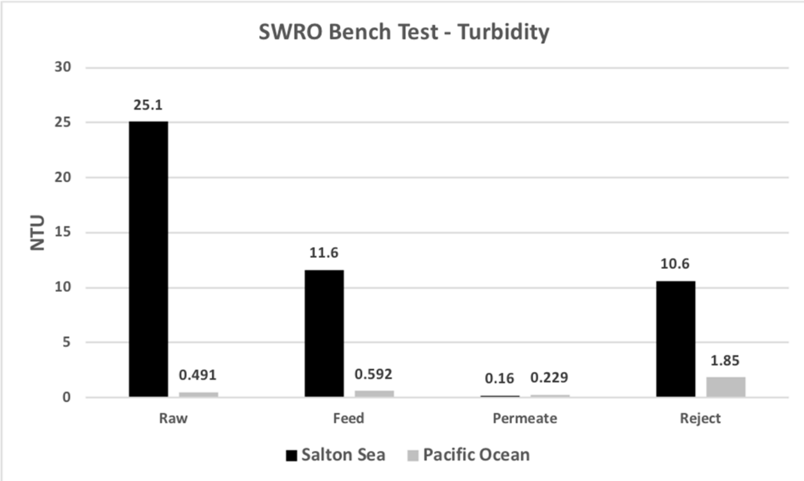

Figure 13. Turbidity raw water, SWRO feed, permeate, and reject flow.

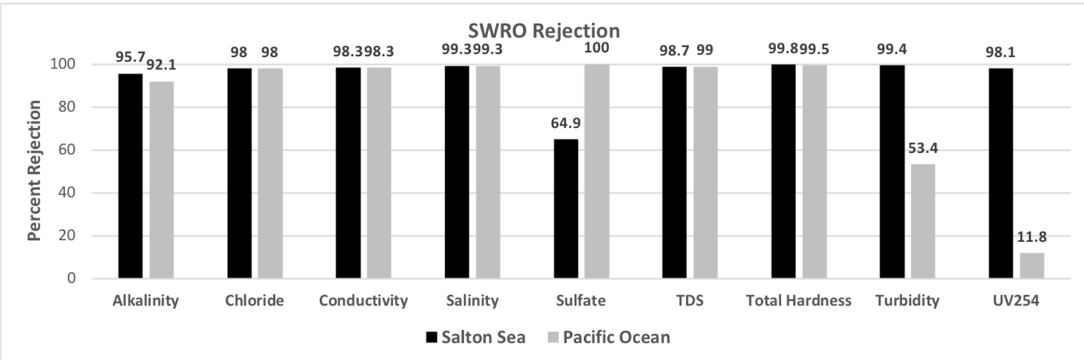

Figure 14. SWRO contaminant rejection.

5. Discussion

High salinity, TDS, sulfate, chloride, and color make treatment of Salton Sea water challenging. High sulfate concentrations coupled with warm temperatures and low redox potentials are present much of the year. These conditions result in sulfate reduction, producing hydrogen sulfide, which effects the iron geochemistry of the lake [9]. Lake mixing events during the summer have adverse effects on the fish and invertebrates in the Sea, as well as migrating birds feeding on them [11].

Coagulation of SSW with alum was found to be most effective for color removal at dosages characteristic of drinking water treatment, although residual color was still very high. Primary production in the Salton Sea is limited by phosphorus. Treating Salton Sea inflow water with alum to remove soluble phosphorus has been considered [29], but requires higher chemical dosages than considered here. The Salton Sea is supersaturated with respect to calcite and gypsum [30,31], potentially limiting the long-term feasibility of SWRO treatment to meet drinking water quality standards.

Drinking water utilities using RO can consistently meet treated drinking water regulatory limits [32,33]. To ensure regulatory compliance, water utilities establish site-specific treated water quality goals that are more strict than regulatory requirements. A comparison of the RO permeate quality achieved here to typical drinking water quality goals is provided in Table 6. Bench tests of SWRO effectively removed contaminants examined here from SSW, except for chloride and TDS. POW permeate only exceeded the chloride water quality goal. Chloride and TDS are regulated in the United States as National Secondary Drinking Water Regulations, which are recommended limits to ensure that drinking water is palatable. Permeate exceeding the recommended limit for chloride and TDS does not pose an adverse health risk, but may affect the taste of the water for some people.

Table 6. RO Permeate Quality Compared to Typical Drinking Water Quality Goals [1].

Constituent	Units	Goal [2]	Salton Sea	Pacific Ocean
Alkalinity	mg/L as $CaCO_3$	NA [3]	12	10
Aeromonas	CFU/mL	None	None	None
Ca^{2+} Hardness	mg/L as $CaCO_3$	NA [3]	14	4
Chloride	mg Cl^-/L	<250	500	380
Color	CU	ND	58	ND
Conductivity	mS	NA	1.65	0.82
HPC [1]	CFU/mL	<500	14	1
pH	units	7.0–8.5 [3]	7.9	7.5
Salinity	ppt	NA	0.4	0.2
Sulfate	mg SO_4^{2-}/L	<250	ND	ND
Suspended Solids	mg/L	None	ND	1
Total Coliform	CFU/mL	None	-	-
Total Hardness	mg/L as $CaCO_3$	50–100	38	24
Total Solids	mg/L	<500	913	410
Turbidity	NTU	<0.3	0.16	0.229
UV254	cm^{-1}	NA	0.013	0.015

Note: [1] NA = not applicable; ND = none detected; - = not tested; [2] Goals based on meeting USEPA drinking water regulations [33,34]; [3] Alkalinity, pH and calcium must be adjusted to render the water noncorrosive.

The U.S. Environmental Protection Agency (USEPA) requires filtration and disinfection treatment for surface water sources of drinking water [33]. Jar tests indicate 0.1 µm pore microfiltration pretreatment will consistently achieve a treated water turbidity limit of 0.3 NTU. The membrane fouling potential is very high for SSW, which must be further assessed. To lessen chemical fouling of RO, softening pretreatment should be considered for lowering calcium and total hardness feed concentrations. The recovery achieved (10 percent) is typical for a single membrane element under these test conditions. The recovery that could achieved by a membrane array treating Salton Sea water must be further evaluated.

In general, high-salinity eutrophic waters are difficult to treat, and are typically avoided as water supply sources. Lower-salinity surface waters, ground waters, and even desalinated sea water are generally preferred when available. The SWRO bench tests conducted here examined only initial contaminant rejection from SSW and POW in the laboratory. Results suggest that treatment of Salton Sea water to meet potable water quality goals is possible, at least at the bench scale. Based on these results, an integrated membrane system consisting of microfiltration, membrane softening, and SWRO is the most promising for treating Salton Sea water. Additional pilot testing at the Salton Sea will be necessary to assess the long-term feasibility of SWRO treatment of Salton Sea water for potential urban water use.

Coastal area desalination plants typically dispose of concentrate by ocean discharge. Concentrate disposal options are more limited for desalination of inland waters such as the Salton Sea, where ocean discharge is not feasible. If large-scale desalination of Salton Sea water is pursued, concentrate disposal must be addressed, regardless of the specific desalination technology selected [34,35]. Concentrate disposal options include well injection, evaporation ponds, or further concentration using vapor compression evaporation. Importation of water from Mexico into the Salton Sea, suggested as a long-term remediation solution [15], could also impact the feasibility of RO desalination and brine disposal for potable water production.

Countries in the Arabian Gulf rely on desalination using distillation technologies (multi-effect and multi-stage) [36]. Should geothermal energy development at the Salton Sea progress to the point of providing an economical supply of energy, distillation technology may provide a viable alternative to RO. Currently, RO is the most economical of desalination technologies for potable water treatment. In December 2015, the largest desalination plant in the United States began operation at Carlsbad, California. The plant provides 50 million gallons per day of RO-treated Pacific Ocean water to the customers of the San Diego County Water Authority [37], further demonstrating the feasibility of SWRO for producing potable water.

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