Peer-reviewed version available at *Water* **2018**, *10*, 324; doi:10.3390/w10030324

Article

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

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Academic Editor: name
Received: date; Accepted: date; Published: date

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). Proposals to desalinate the Salton Sea are expected to lower the equilibrium salinity from 45 ppt to 3 ppt yielding significant benefits for ecological restoration. High salinity eutrophic waters such as the Salton Sea are difficult to treat yet more desirable sources of drinking water are not always available. Jar tests were performed to evaluate the treatability of Salton Sea water for potential urban water use by coagulation using aluminum chlorohydrate, ferric chloride and alum. Coagulation-sedimentation 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 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

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], ongoing or reoccurring drought conditions [4], or from 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 Jan. 1, 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 [8,9,10,11]. Despite being a hypereutrophic, hypersaline water body, the Salton Sea provides a significant ecological function and is a vital habitat for migrating birds. Development

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and implementation of plans to remediate the Salton Sea ecosystem has been an ongoing challenge for the California Dept. of Water Resources [12] and the approximately 650,000 people living with the air basin impacted by dust from the sea [13]. Stakeholders have proposed various alternatives to remediate the ecosystem including construction of a 558 MGD desalination reverse osmosis (RO) plant to produce water to be used within the Salton Basin [14].

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 preferred but are not always available. Previous proposals to desalinate the Salton Sea are expected to lower the equilibrium salinity from 45 ppt to 3 ppt [14]. This would have significant benefits for ecological restoration but is still too high for the Salton Sea to serve as a potential urban water supply. This present study explores the treatability of Salton Sea water for potential urban water use when other options are limited or non-existent.

2. Materials and Methods

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

In August 2017 multiple 5-gallon 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.

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.

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 [15]. 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 minutes, slow mixing for 30 minutes (tapered at 10 minute intervals); and settling for 45 minutes. 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. 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.

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	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

[1] HPC = heterotrophic plate count; Filt = 30 µm filtered; Perm = RO permeate; Reject = RO brine flow.

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 brine 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.

Feed water was pumped through the SWRO system at 20 L/h for 60 minutes at 58 bar to 66 bar transmembrane pressure (TMP). Composite samples were taken for analysis of the SWRO feed water, permeate and reject stream. TMP, permeate flow and reject water flow were monitored during the test.

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Table 2. Bench Scale SWRO System Specifications [16].

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)
Membrane Type	Thin-Film Composite
Membrane Surface Area	1 m^2 (estimated)
Pre-filter	Pentek® 5 μm polypropylene (Pentair)
High-Pressure Pump	708 Titan Series (Aqua Pro Pumps)
Max. Operating Pressure	1000 psi
Max. Operating Temp.	45°C
Design Flux	30 Lmh (estimated)
Design Product Flow	0.8 m^3/d (210 gpd)
Max. Feed Turbidity	1 NTU
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)

[1] Silt Density Index.

3. Analytical Methods

All analyses were performed at the CBU environmental engineering laboratory. The analytes and analytical methods used are presented in Table 2. *Standard Methods* [17], US Environmental Protection Agency (EPA) methods [18], or their equivalent as developed by Hach [19] and Micrology Laboratories [20] 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) and 254 nm (UV254). All experiments and analyses were performed at laboratory temperature (22°C).

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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

[1] Micrology Laboratory, Goshen, Indiana; * Modified pour plate method developed by the manufacturer.

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.

4.1. Cartridge Filteration

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.

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	38000	25400	500	27700
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	20800	17700	ND	19500
Suspended Solids	mg/L	44	--	ND	162
Total Coliform	CFU/mL	37	--	--	--
Total Hardness	mg/L as $CaCO_3$	17500	9300	38	10900
Total Solids	mg/L	70200	--	913	77136
Turbidity	NTU	25.1	11.6	0.16	10.6
UV254	cm^{-1}	0.696	0.69	0.013	0.815

[1] HPC = heterotrophic plate count; Filtered = 30 µm filtered; Permeate = RO permeate; Reject = RO brine; ND = none detected

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	18800	18300	380	24000
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	39443	--	410	47121
Turbidity	NTU	0.491	0.5	0.229	1.85
UV254	cm^{-1}	0.017	0.016	0.015	0.13

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

4.3. Jar Test Results

The Salton Sea is highly colored. Results of jar testing are presented in Figures 1 through 6. Coagulation-sedimentation proved to be relatively ineffective for lowering turbidity with no clear optimum dose for any of the coagulants tested (Figures 1, 2 and 3)).

ACH generally increased pH (Figure 3) and alkalinity (Figure 4) whereas ferric and alum lowered pH and alkalinity. Alum was most effective for color removal (28 percent) at a dose of 40 mg/L.

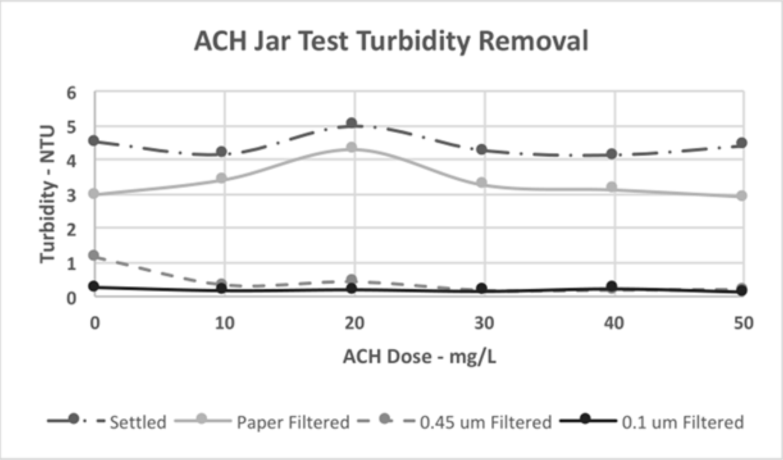

Figure 1. Turbidity after settling versus ACH dose and filtering through 8 μm filter paper, a 0.45 μm membrane filter and a 0.1 μm membrane filter.

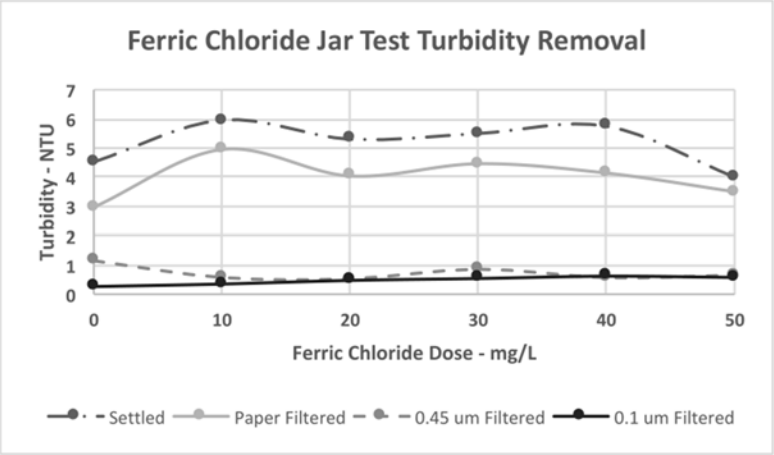

Figure 2. Turbidity after settling versus ferric dose and filtering through 8 μm filter paper, a 0.45 μm membrane filter and a 0.1 μm membrane filter.

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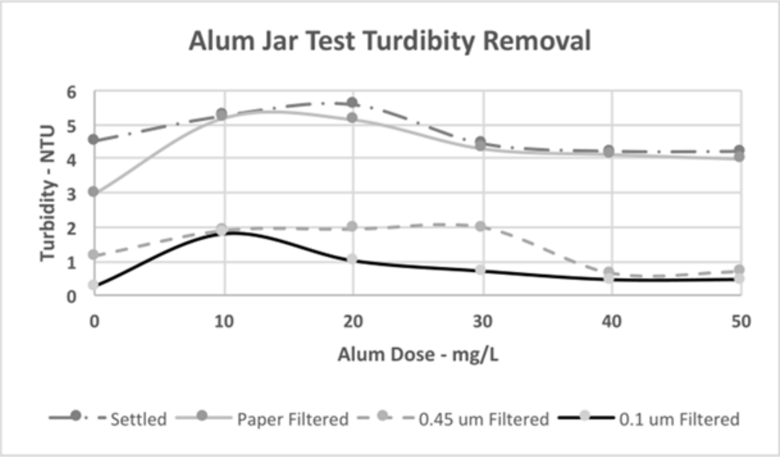

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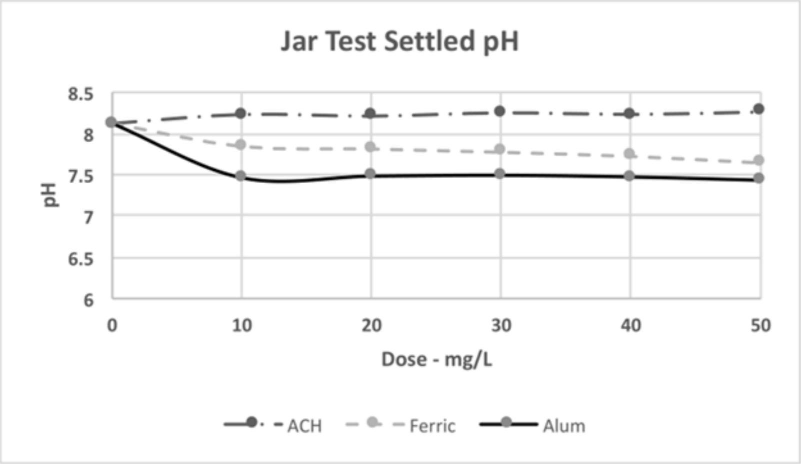
160 **Figure 3.** Turbidity after settling versus alum dose and filtering through 8 μm filter paper, a 0.45 μm
161 membrane filter and a 0.1 μm membrane filter.



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163 **Figure 4.** Jar test settled pH versus coagulant dose.

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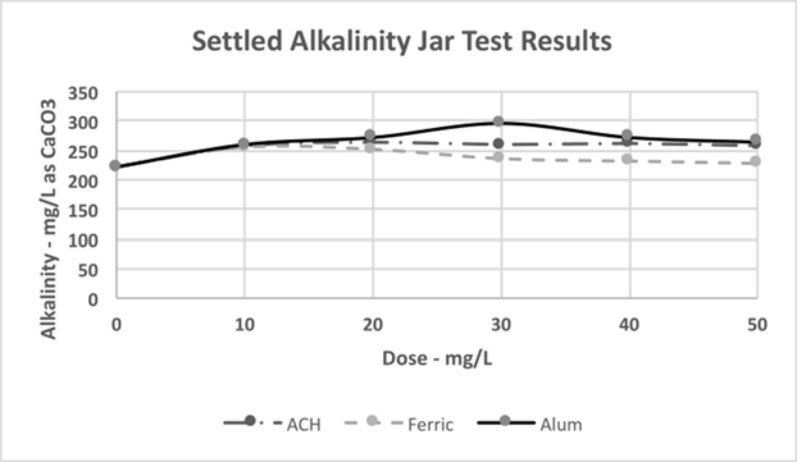

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166 **Figure 5.** Jar test settled alkalinity versus coagulant dose.

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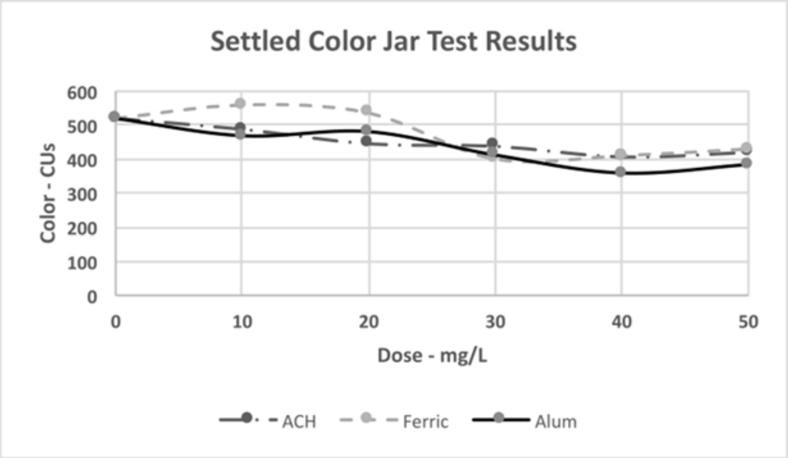

Figure 6. Jar test settled color versus coagulant dose.

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 1), conductivity (Figure 2), total dissolved solids (TDS) (Figure 3), chloride (Figure 4), sulfate (Figure 5), and turbidity (Figure 6) were all removed. SWRO contaminant rejection is summarized in Figure 7.

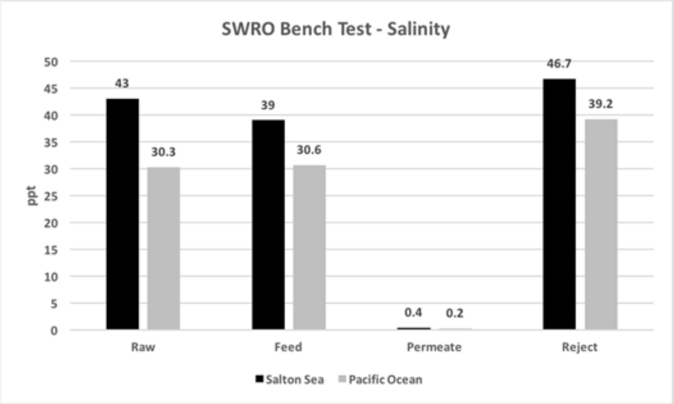

Figure 1. Salinity of raw water, SWRO feed, permeate and reject flow.

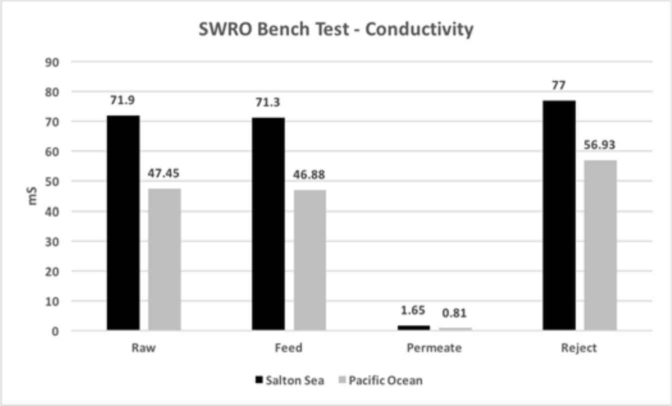

Figure 2. Conductivity of raw water, SWRO feed, permeate and reject flow.

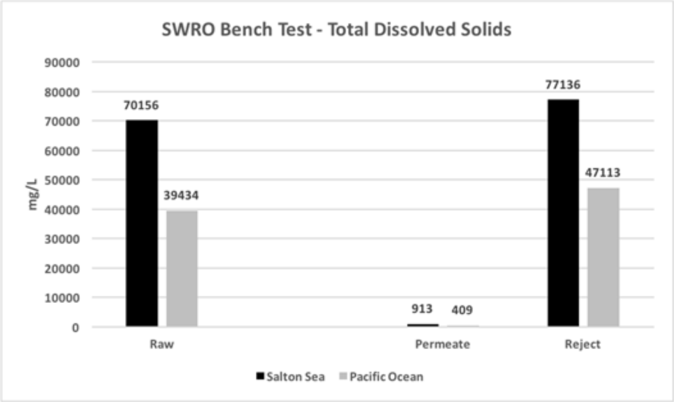

Figure 3. Total Dissolved Solids (TDS) of raw water, SWRO feed, permeate ad reject flow. TDS = total solids – suspended solids

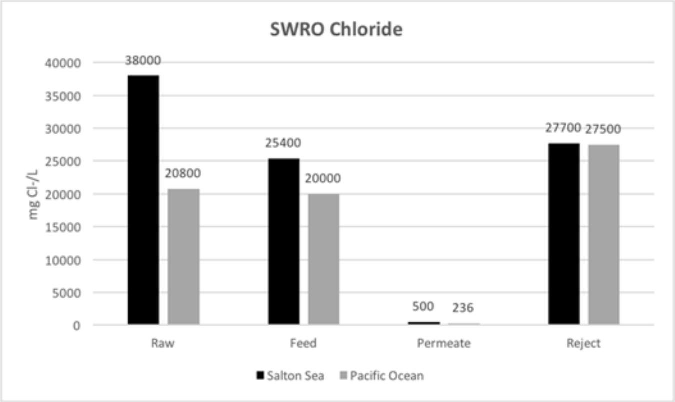

Figure 4. Chloride of raw water, SWRO feed, permeate and reject flow.

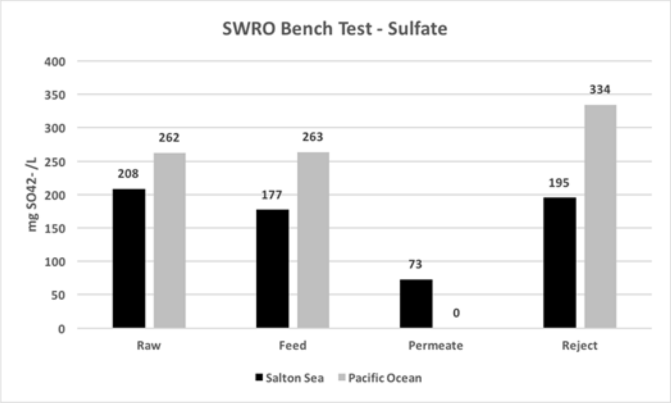

Figure 5. Sulfate of raw water, SWRO feed, permeate and reject flow.

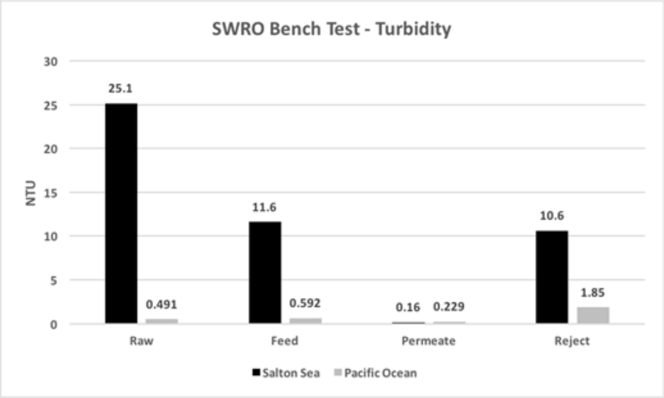

Figure 6. Turbidity raw water, SWRO feed, permeate and reject flow.

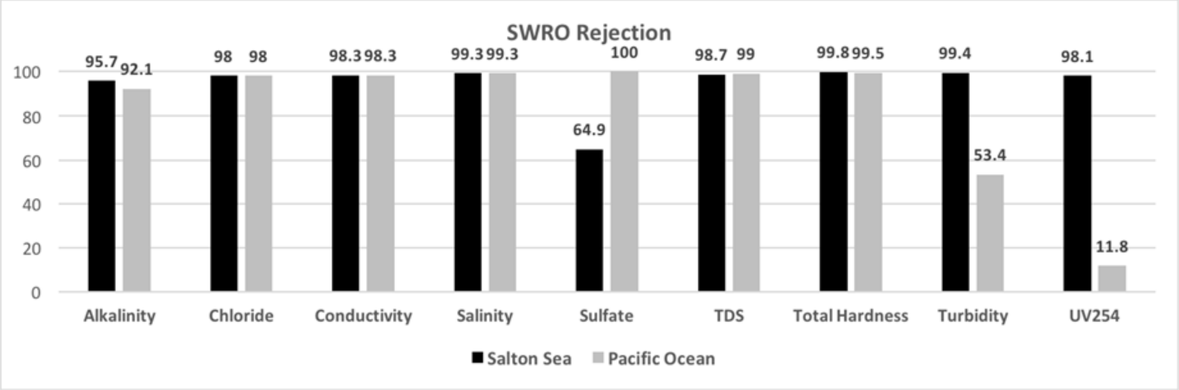

Figure 7. SWRO contaminant rejection.

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 to 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 [21] but requires higher chemical dosages than considered here. The Salton Sea is supersaturated with respect to calcite and gypsum [22] which will effect long-term feasibility of SWRO.

Microfiltration is necessary to remove turbidity to drinking water standards. Bench tests of SWRO effectively removed salinity and other contaminants examined here from both SSW and POW to within or very close to World Health Organization drinking water guidelines [23].

The SWRO bench tests conducted here examined only initial contaminant removals from SSW and POW. The membrane fouling potential is very high for SSW which must be further assessed. Based on these results an integrated membrane system consisting of microfiltration, membrane softening and SWRO is the most promising for treating Salton Sea water for potential urban water use. Additional pilot testing will be necessary to assess the long-term feasibility of membrane treatment of Salton Sea water for potential urban water use.

Acknowledgments: This research was financially supported in summer 2017 by a micro-grant from the CBU Gordon and Jill Bourns College of Engineering. No funding was received for covering the costs to publish in open access.

Conflicts of Interest: The author declares no conflict of interest. The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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