Chloride Reduction in Municipal Wastewater Effluent with Membrane Brine Concentration

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Abstract

This paper presents a novel solution for reducing effluent chlorides or for production of potable water from wastewater treatment plant (WTP) effluent. It combines nanofiltration (NF), reverse osmosis, softening and CounterFlow Reverse Osmosis (CFRO) technologies to achieve over 99% recovery, minimizing final brine flow while producing drinking-quality fresh water. The process is being considered for implementation at a WTP in the Western United States.

Introduction

As freshwater resources dwindle, water conservation becomes essential, especially in water-stressed regions. One of the impacts of reduced freshwater inflow into municipal wastewater treatment plants (WTPs) is that sewage is becoming saltier. Because WTPs do not remove dissolved salts, chloride concentrations in the effluent from these plants is increasing. Chloride levels in river valleys and groundwater basins in some parts of the country exceed regional water quality objectives and impair beneficial uses for agricultural supply. Partial desalination of WTP effluent has been identified as a promising approach to reduce chloride levels and their environmental impact.

Reverse osmosis (RO) is an effective means to desalinate water and concentrate and eliminate dissolve species, including chloride. RO is the most widely-applied desalination method, however it generates a substantial stream of brine concentrate that represents an environmental hazard and a significant cost. Typically, reduction of this brine through additional concentration beyond about 80,000 mg/l total dissolved solids (TDS) is not possible with RO equipment due to scaling of membrane surfaces by precipitation of sparingly soluble salts and the required pressures, which can exceed available equipment limitations. Existing brine concentration technologies use heat, require high capital costs and consume significant amounts of energy, and therefore are generally not acceptable in most potential applications.

This paper presents a novel method of desalinating municipal effluent. With a combination of nanofiltration (NF), reverse osmosis, softening and CounterFlow Reverse Osmosis (CFRO) technologies, recovery rates of over 99% from municipal effluent can be achieved. The result is a low-chloride product stream for discharge or beneficial use, a dry filter cake for landfill disposal and a small flow rate of brine concentrate with a TDS of up to 250,000 mg/l.

The process described in this paper is being considered for implementation at a WTP in the Western United States. It represents a novel integrated membrane-based effluent concentration system for reducing chloride in treated municipal effluent that minimizes the amount of residual brine requiring offsite disposal and minimizes energy consumption. Alternately, the system could be used

as a high recovery water reclamation system to produce fresh water from wastewater or brackish groundwater while minimizing residual brine and energy consumption.

Previous Work

Although membrane desalination of municipal effluent has been practiced for decades, its application for chloride reduction in effluent to be discharged to the environment is relatively recent. A project by the Los Angeles County Sanitation Districts ("the Districts") that began development about 8 years ago proposed an innovative approach to address the problem (Mansell 2015). The major goals and constraints on the Districts' project design were:

- Chloride concentration reduction from approximately 126 mg/l to less than 100 mg/l to comply with regulatory requirements
- Brine minimization due to lack of affordable disposal options
- No sludge generation due to operational preference

The process design initially proposed and piloted for the project featured a combination of microfiltration (MF), NF and high recovery RO. The MF rejected suspended solids and some organics back to the WTP. The NF rejected divalent ions and most of the rest of the organics to the river without substantially increasing the chloride concentration. The softened NF permeate was subjected to additional desalination concentration in a RO system operating at about 96% recovery. The low chloride content of the RO permeate diluted the NF reject, which, when combined with the balance of the untreated effluent, met the chloride concentration discharge limit. The RO reject, highly concentrated in chloride and other constituents, was to be disposed by deep well injection. However, this design was rejected by a public adverse to the risks of deep well injection in earthquake country, thereby adding a fourth constraint to the project.

The revised project scheme is illustrated in the following figure. The anticipated recovery rate of the system, computed by dividing the river discharge flowrate by the feed flow rate, is 97.8%, corresponding to about half as much final brine as the original design. The brine produced was to be loaded into tanker trucks and hauled to a regional ocean discharge interceptor site.

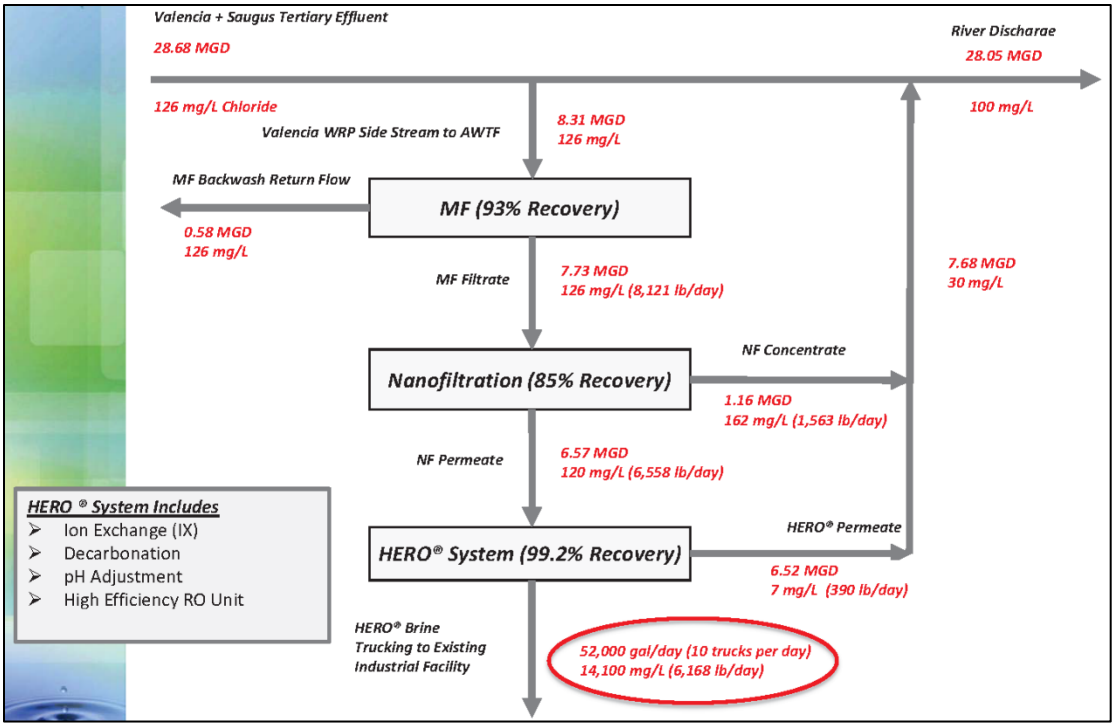


Figure 1 – Los Angeles County Sanitation Districts Chloride Reduction Scheme (Mansell 2016)

A partial analysis of the feedwater was as follows:

Table 1 Los Angeles County Sanitation Districts Feedwater Analysis (Mansell 2016)

Constituent	MF Filtrate (mg/L)	NF Permeate (mg/L)	Removal (%)
TOC	5.1	0.50	90
TDS	945	483	48
Calcium	84	30	64
Magnesium	25	7	72
Barium	0.01	0.0032	71
Strontium	0.69	0.26	62
Total Hardness	313 (as $CaCO_3$)	105 (as $CaCO_3$)	67
Sulfate	291	15	95
Phosphate	5.4	0.36	93
Alkalinity	262 (as $CaCO_3$)	134 (as $CaCO_3$)	49
Chloride	126	120	5
Silica	23	21	9

Although the hardness, alkalinity and silica concentrations in the NF permeate were far below saturation levels, after the proposed 120x concentration factor, they posed significant scaling risks in the RO process. Therefore, ion exchange, decarbonation and pH elevation were applied

to reduce hardness and silica in the NF effluent prior to RO concentration. The projected silica concentration in the final brine was to be as high as 2,500 mg/l at a pH of 11.

There are several significant challenges this proposed system could face. Even at 97.8% recovery, the amount of brine produced in the full-scale plant will fill about 6 tanker trucks per day. Any variations in system performance that could result in a decrease in recovery, such as membrane fouling or scaling, water composition variation, or operator error, for example, could significantly increase the number of daily trucks required. The proposed disposal site is about 45 miles away from the project site along highways notorious for heavy traffic. The final RO stage is to operate at a higher pH than most RO membranes are rated for, likely shortening membrane life and posing a risk of membrane failure. Finally, possible instability in the chemistry of the final brine could result in precipitation in the tanker trucks or in the ocean discharge line.

It must be emphasized that the above considerations are based on information that is five years or more old. The process design and the risks described may have changed or been mitigated with process features unknown to the author.

Proposed Improved Design

Many of the challenges described above can be addressed by selectively removing sparingly soluble minerals prior to desalination. In addition, the incorporation of a novel membrane brine concentration process offers the possibility of reducing the flow of brine residual by up to a factor of three compared to high recovery reverse osmosis. Such an approach has been proposed for an a different WTP facing similar constraints on chloride discharge and brine disposal as described above.

Overview

The proposed advanced chloride reduction (ACR) process scheme is illustrated in the figure below.

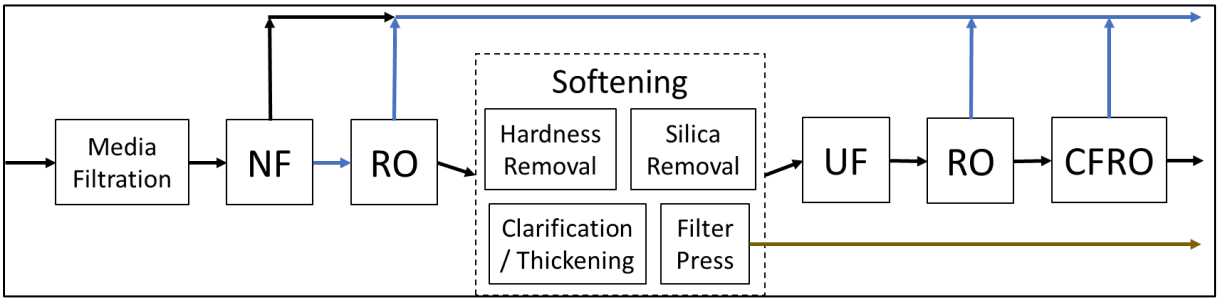


Figure 2 Advanced Chloride Reduction System with Membrane Brine Concentration

The first three ACR unit operations perform similar functions as the first steps of the Districts' process. Media filters reject suspended solids and oil and grease back to the WTP. NF is used to reduce divalent salts, disinfection by-products and organic matter, rejecting them to the river while still at low concentration without concentrating chloride. NF permeate is concentrated by a first RO unit. The RO brine is then treated to precipitate sparingly soluble salts, which are pressed into solid

cake for landfill disposal. The removal of these materials enables additional desalination of the softener effluent with reduced risk of scale deposition. UF is applied to polish the softening effluent, rejecting residual solids back to the softening process. A high-pressure RO step increases TDS to about 63,000 mg/l, producing additional low-chloride permeate to blend with the river discharge stream. Finally, a Counter-Flow Reverse Osmosis (CFRO) membrane brine concentration unit extracts a final measure of low-chloride permeate, producing 200,000 mg/l TDS brine for offsite disposal. Desalinated permeate from all the RO units blends with the NF reject and untreated municipal effluent to meet the chloride discharge concentration requirement.

Details of the unit operations and projected system performance are provided in the sections below.

Nanofiltration

The composition of the feed to the NF is given in Table 2 below. Acid, antiscalant and sodium metabisulfite are dosed to minimize the risk of calcium carbonate, calcium sulfate and silica scaling and to remove any residual chlorine. The NF unit, equipped with three membrane stages, operates at 85% recovery with an average flux of 11.5 gallons per square foot per day (gfd). These conditions provide optimum mineral rejection without significantly concentrating chloride. Specifically, calcium, magnesium and sulfate are reduced by about a factor of three. In addition, most residual organics are eliminated from the downstream processes.

Brackish Water Reverse Osmosis

NF permeate is concentrated at 90% recovery, 15.4 gfd average flux and a maximum pressure of about 150 psi in a brackish water RO (BWRO) unit. The BWRO can be configured conventionally, with three stages operating in a cascade, or as a single stage operated in semi-batch mode. The Districts' piloting work demonstrated that semi-batch RO offers the advantage of enhanced silica and calcium carbonate scale resistance (Mansell 2015). The BWRO brine produced is near or slightly above saturation with these constituents. Concentrating prior to softening makes the precipitation reactions quicker and reduces the required capacity of the softening tanks and pumps.

Softening

BWRO brine is treated in the softening system to remove of calcium, silica, barium and phosphate. The softener consists of two reaction tanks, a lamella clarifier, a thickener and a filter press. Lime and soda ash are added in the first reaction tank. Magnesium chloride and caustic soda are added in the second reaction tank. The solids are flocculated and settled in the clarifier. Clarifier bottoms are thickened with polymer before being fed to the filter press. The filter press traps solids in a filter cake, which is periodically unloaded into a roll off bin.

Ultra-Filtration

Overflow from the clarifier is fed to the ultra-filtration (UF) system which removes any suspended solids before the effluent is fed to the downstream RO units. The UF system operates at 91% recovery and about 34 gfd flux. Backwash reject from the UF system is returned to the softener.

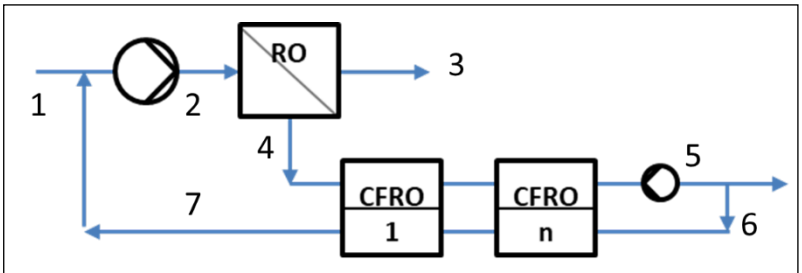
High-Pressure Reverse Osmosis

UF filtrate is further concentrated in a high-pressure RO (HPRO) unit which operates at 63% recovery, 15 gfd and up to 870 psi feed pressure. The resulting permeate has a TDS of about 86 mg/l and a chloride concentration of about 47 mg/l. In a typical desalination operation, this TDS would likely be suitable for freshwater applications, but for this chloride reduction operation, additional chloride reduction with permeate polishing is required.

CounterFlow Reverse Osmosis

Reject water from the HPRO system at about 63,000 mg/l TDS is fed to the CFRO membrane brine concentrator system. Gradiant's CFRO process is a non-evaporative, membrane-based method for desalinating brines (Stover 2018). Like conventional RO, the CFRO process uses pressure to drive water across a semi-permeable membrane against the osmotic pressure difference between the feed and permeate streams, removing dissolved salts. What makes the CFRO process unique is the introduction of a saline solution to the permeate side of the membrane. This reduces the osmotic pressure barrier, which lowers the feed pressure required to drive permeate flow. As a result, ultra-saline feeds can be treated at low enough hydraulic pressures to enable the use of standard RO equipment.

A sketch of a typical CFRO process configuration is given in Figure 3 with illustrative flows and pressures.



stream	1	2	3	4	5	6	7
flow	100	250	75	175	79	54	150
pressure, psi	15	1,100	0	1,000	70	70	15
salinity, g/l	63	68	0	90	200	200	72

Figure 3 CFRO Process with Illustrative Flows and Pressures

With reference to Figure 3, stream 1 is brine from the upstream HPRO unit. It is combined with stream 7, the dilute sweep stream from the CFRO membranes, pressurized and fed to the preconcentrating RO unit as stream 2. Permeate from the preconcentrating RO membranes (stream 3) merges with permeate from the HPRO unit to feed a second pass polishing RO unit (not shown). Reject from the polishing RO unit is returned to the feed of the HPRO unit. Brine from the preconcentrating RO unit is fed directly to the counterflow RO unit (stream 4) without breaking or boosting pressure. After cascading through multiple CFRO stages, brine from the last CFRO stage is depressurized through an energy recovery device or throttle valve (stream 5). A portion of the depressurized brine is rejected from the system for disposal or downstream processing. The rest of the brine is applied to the permeate side of the brine concentration

membranes to serve as sweep solution (stream 6). Sweep solution cascades from the last to the first brine concentration stage counter-current to the feed flow. Fully diluted sweep solution is merged with the feed to the preconcentrating RO unit (stream 7). The CFRO process ultimately produces two product streams: desalinated permeate and concentrated brine with a salinity of up to the saturation limit of the dissolved salt.

Anticipated Performance

The ACR was designed to desalinate 1.44 million gallons per day (MGD) of municipal effluent, which is about 31% of the 4.70 MGD of total effluent flow from the WTP. The ACR system is designed to operate at 99.6% recovery, producing just over 2,800 gallons per day of final brine. The approximate concentrations of major constituents in the feed, blended effluent and final brine streams is listed in Table 2.

Table 2 Advanced Chloride Reduction System Overall Stream Compositions

Parameter	Unit	Feed	Effluent	Brine
TSS	mg/L	1.06	0.0	0.0
Turbidity	NTU	0.28	0.0	0.0
Oil & Grease	mg/L	2.15	0.0	0.0
BOD	mg/L	1.69	0.0	0.0
TOC	mg/L	0.6	0.0	0.0
NH_4^+	mg/L	1.4	1.0	235
Na^+	mg/L	170	66.4	74,819
Mg^{+2}	mg/L	54.3	41.8	1.7
Ca^{+2}	mg/L	181	128.4	61.1
CO_3^{-2}	mg/l	2.88	0.1	1.0
HCO_3^-	mg/l	396	99.3	241
NO_3^-	mg/l	3.6	0.5	1,562
F^-	mg/l	0.5	0.0	13.8
Cl^-	mg/l	133	19.1	92,318
SO_4^{-2}	mg/l	448	507.6	30,413
PO_4^{-3}	mg/l	3.7	1.9	197
SiO_2	mg/l	39.2	10.7	135
CO_2	mg/l	7.7	91.9	59.3
TDS	mg/l	1,367	881	200,000

The cost of treatment over a range of possible final brine concentrations is presented in Figure 4. Capital costs were amortized over 20 years at 6% interest. For producing 200,000 mg/l TDS

brine, ACR system capital cost is estimated at $0.70, operating at $1.35 and total cost $2.15 per 1000 gallons of water treated.

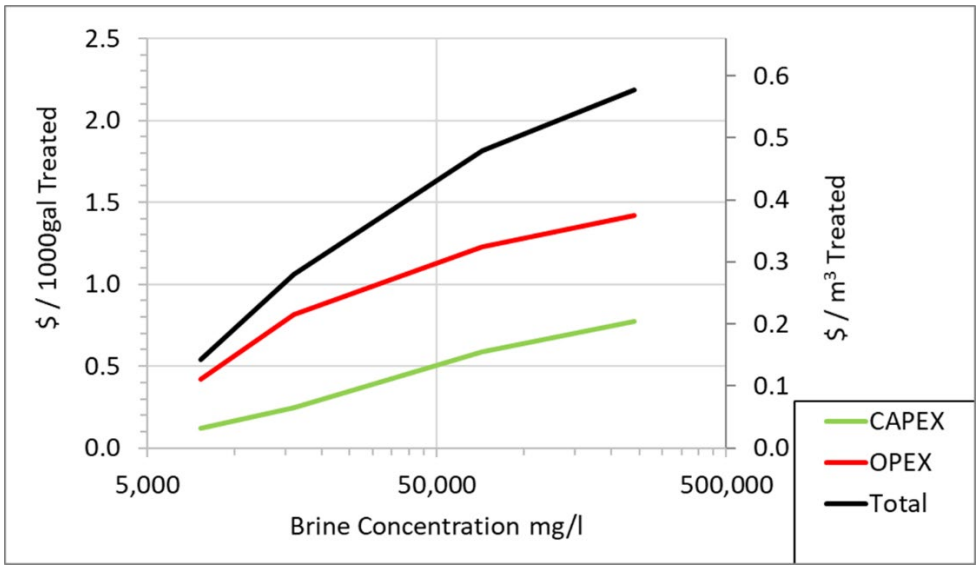


Figure 4 Cost of Advance Chloride Reduction Treatment as a Function of Brine TDS

The data charted in Figure 4 do not include the cost of brine disposal and, therefore, do not illustrate the cost savings potential of minimizing brine flow. The only means of brine disposal available to the ACR project site is hauling and offsite disposal, which costs a minimum of $30/1000 gallons. Figure 5 presents combined treatment and brine disposal costs as a function of brine concentration.

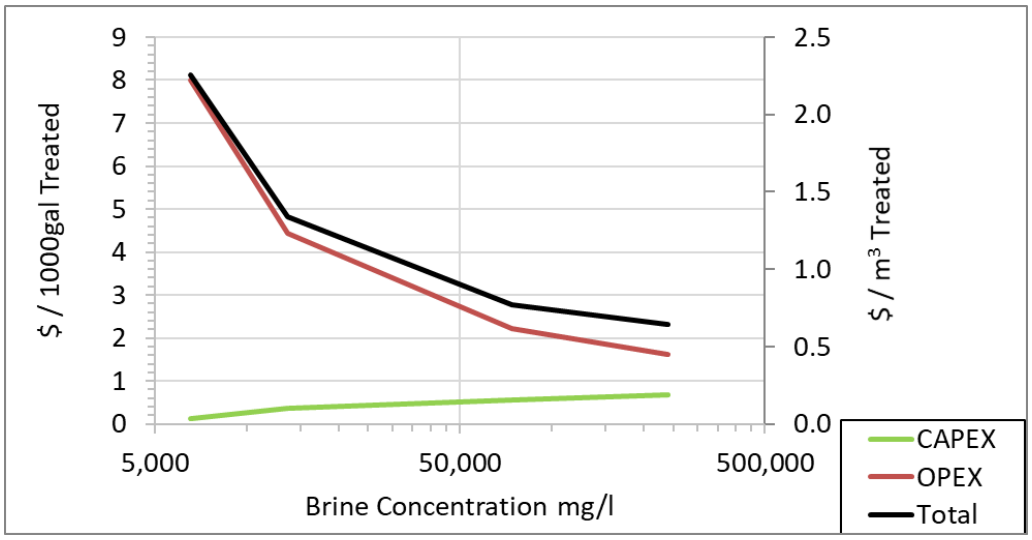


Figure 5 Cost of Water Treatment Including Brine Disposal as a Function of Brine TDS

The total cost of ACR treatment to 200,000 mg/l TDS brine is approximately $2.40 per 1000 gallons treated. Without softening and membrane brine concentration, the maximum brine TDS achievable is about 60,000 mg/l and the total cost would be over $3.00 per 1000 gallons.

Implications

Although this paper analyzes the use of high recovery operation and brine minimization for chloride reduction, the same process can be used for fresh water production from wastewater or a saline water source with the same economics and benefits. Making high recovery operation feasible can enable use of saline water sources that could not previously be utilized due to high brine management costs. This has potential significance for multiple industrial sectors including power, mining, textiles, electronics, pharmaceuticals, food and beverage and inland desalination applications. If applied to seawater desalination, membrane brine concentration can double a plant's drinking water production without new intake, outfall or pre-treatment costs or impacts. In addition, existing desalination systems facing brine disposal constraints or feedwater supply limitations can implement some or all of the ACR treatment processes to increase productivity and decrease costs.

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