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Comparison of slow sand filtration and microfiltration as pretreatments for inland desalination via reverse osmosis

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HIGHLIGHTS

- MF and SSF both produced water that satisfies feed water quality requirements for RO treatment (SDI $\leq$ 5).
- SDI values in MF treated waters were consistently $\leq$3.0 and lower than SSF SDI values.
- Long-term RO performance was more stable following MF than SSF pretreatment.
- The economics of MF and SSF as pretreatments for RO were nearly equivalent.

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ABSTRACT

A pilot study was conducted from October 2007 to November 2010 to establish the long-term feasibility of using reverse osmosis (RO) treatment to manage salt levels in Central Arizona Project water. Pretreatments consisting of microfiltration (MF) and slow sand filtration (SSF) were compared based on performance—turbidity removal, silt density index (SDI), volume treated between cleaning events and protection of downstream RO—during side-by-side operation over a yearlong period. SSF always produced feed water that was suitable for RO treatment (SDI < 5). However, MF consistently provided filtrate with SDI < 3, and long-term RO performance improved significantly with MF as pretreatment. Although the economic costs of MF and SSF pretreatments are similar; MF is preferred based on the quality of treated water and stability of downstream RO operation.

1. Introduction

The lower Colorado River basin is the only major United States watershed in which annual water consumption exceeds regional runoff. Regional demands for water are satisfied, at least for the time being, by importing and conserving water, treating waters of initially impaired quality and water marketing [1,2]. Regional water resources that are of impaired initial quality, e.g. municipal wastewater and brackish ground water, will play an increasingly important role in southwestern water management.

The importance of the Colorado River to the water resources portfolios of southwestern states has become axiomatic. With an average

Abbreviations: A, water transport coefficient, m/s/Pa; A_m, initial water transport coefficient, m/s/Pa; A_{MF}, area of microfilter, m^2; A_{SSF}, area of slow sand filter, m^2; ANOVA, analysis of variance; B, salt transport coefficient, m/s; BOR, Bureau of Reclamation; CAP, Central Arizona Project; C_C, cost of construction, \$; C_G, cost of gravel, \$/ton; CIP, cleaning in place; C_L, cost of land, \$/m^2; CMF, continuous microfiltration; C_S, cost of sand, \$/ton; EDS, energy dispersive x-ray spectrometer; F, permeate flux, $m^3 s/m^2$; F_{30}, annuity factor for 30 years; f_C, frequency of cleaning, #/year; f_R, frequency of re-sanding, #/year; K_{SO}, solubility constant; M, microfiltration unit cost, \$; MCL, maximum contaminant limit; MF, microfiltration; n, number of samples; NSSF, north slow sand filter; NTU, nephelometric turbidity units; P_{avg}, feed average pressure, Pa; PF, plugging factor, %; P_P, permeate feed, Pa; P_W, personnel wage, \$/year; Q_{SO}, solubility product; Q_{TP}, treatment plant flow rate, m^3/day; r, discount operator, %; R_f, fouling resistance, s·Pa/m; R_m, clean membrane fouling resistance, s·Pa/m; R_{obs}, observed membrane fouling resistance, s·Pa/m; SEM, scanning electron microscopy; S.D., standard deviation; SDI, silt density index; SSF, slow sand filter; SSSF, south slow sand filter; T, temperature, [C]; TDS, total dissolved solids, mg/L; t, time, min; T_{CSSF}, time to clean the slow sand filter, h/m^2; TFC, thin film composite; TMP, transmembrane pressure, kPa; T_{RSSF}, time to re-sand the slow sand filter, h/m^2; ULP, ultra low pressure; XRD, x-ray diffraction; ε_G, porosity of gravel, [−]; ε_S, porosity of sand, [−]; π_{avg}, feed osmotic pressure, Pa; π_p, permeate osmotic pressure, Pa; ρ_G, density of gravel, kg/m^3; ρ_S, density of sand, kg/m^3.

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annual flow of roughly 1.9×10^{10} m^3 (15 million acre-feet), the Colorado River is the most important source of water in the southwestern United States, providing water for tens of millions of people from San Diego to Denver [1]. Forty percent of Arizona's water supply is taken from the Colorado River. In all southwestern water supply scenarios, effective utilization of Colorado River water is among the keys to regional water resources sustainability. In some respects, however, water quality in the lower Colorado River already fails to meet sustainability objectives. In the lower Colorado River basin, the average total dissolved solids (TDS) level is approaching 750 mg/L [3], so that the Central Arizona Project (CAP) canal transports about 200,000 metric tons of salt into the Tucson, AZ, area each year. Only a small percentage leaves as surface flow or groundwater underflow. Consequently, the average TDS concentration in major aquifers serving the Tucson municipal area is expected to increase at a rate of 5 mg/L year [4], leading to long-term salinity and soil fertility issues. As a point of reference, the secondary MCL for TDS in drinking water is 500 mg/L [5], and waters with TDS concentrations greater than 1000 mg/L are considered brackish [6].

Salinity management in CAP water has been seriously considered in central and southern Arizona [6]. Reverse osmosis (RO) and nanofiltration (NF) are commonly used to separate salts from water when initial TDS levels are below those of seawater. Both RO and NF processes, however, require pretreatment of the feed water to remove membrane foulants and limit membrane scaling. Of the several available methods, slow sand filtration (SSF) and microfiltration (MF) were chosen here for comparison. Previous work by utility and agency partners (Tucson Water, Northwest (Tucson) Water Providers, and Bureau of Reclamation (BOR)) indicated that both pre-treatments controlled fouling during RO treatment of CAP water and that, land permitting, SSF was significantly less expensive [7]. This conclusion arose from a test performed over 7 months of continuous operation that did not include comparisons based on contemporary operation of pretreatment alternatives or investigation of seasonal factors. Slow sand filtration has not been extensively used for RO pretreatment, but was studied previously as a pretreatment for ultrafiltration. SSF improved the performance of ultrafiltration by delaying the normal loss of permeate flux [8,9]. When used for RO pretreatment, SSF consistently produced water with silt density index (SDI) values below membrane manufacturers' recommendation of 5.0%/min for RO [7,10,11]. On the other hand, MF has been widely studied as a pretreatment for RO [12–19].

Typical design/process parameters for SSF and MF are as shown (Tables 2 and 3). In SSF, sand supports the development of a schmutzdecke, a biologically active surface layer in which suspended particles and dissolved organics can be biochemically degraded [20–22]. Biological growth in the schmutzdecke eventually impedes infiltration to a degree that requires the filter surface to be renewed by removing a thin layer of sand.

MF uses micro-porous membranes to strain particles from suspension. This is a completely mechanical process in that no chemical or biological activity is involved. MF utilizes the largest pore size range of the pressure membrane family, from 0.1 μm to 10 μm, and operates at the lowest pressure [15,23]. At filter pore sizes <0.2 μm, microfiltration removes bacteria, some viruses and colloidal silica as well as larger particles that might foul RO membranes.

Here we describe the results of a pilot study in which SSF and MF were used as pretreatments for RO treatment of CAP water in the Tucson, AZ area. Pretreatment effectiveness was compared in terms of yearlong pre-RO water quality characteristics, sustained (downstream) RO performance and cost.

2. Experimental

Calcium sulfate, calcium carbonate and barium sulfate solubilities will be exceeded in brines derived from RO treatment of CAP water at 80% RO water recovery (Table 1). CAP water arrives in Tucson oversaturated with respect to barium sulfate, and it has been suggested that $BaSO_4$ precipitation limits recovery during RO treatment [24].

Table 1
Concentration/solubility data for CAP water ion pairs that may contribute to membrane scaling.

Precipitate	Ion concentration in CAP water	log (ion product) in CAP water	log $K_{SO}^{(b)}$	Degree of super saturation following RO treatment[(c)]
$BaSO_4(s)$	$[Ba^{+2}] = 1.11 \times 10^{-6}$ M $[SO_4^{-2}] = 2.66 \times 10^{-3}$ M	−7.13	−9.96	673.20
$CaSO_4(s)$	$[Ca^{+2}] = 1.87 \times 10^{-3}$ M	−3.91	−4.85	8.81
$CaCO_3(s)$	$[CO_3^{-2}] = 6.88 \times 10^{-6}$ M[(a)]	−6.49	−8.48	97.19

(a) Based on 118.05 mg/L carbonate alkalinity as HCO_3^- and pH = 7.88.
(b) [25] & [28].
(c) Calculated as Q_{SO}/K_{SO}. The value represents the approximate degree of oversaturation in the RO brine produced from CAP water at 80% recovery.

The pilot-scale desalination facility was located 20 miles northwest of Tucson, adjacent to the CAP Canal. Unit operations (Fig. 1) consisted of slow sand filtration (SSF) or microfiltration (MF); chemical addition —15 mg/L of sulfuric acid, to maintain the RO feed water at pH ~6.8, commercial antiscalant (Flocon 135, 3.5 mg/L), NaOCl (1.4 mg/L) plus $(NH_4)_2SO_4$ (2.0 mg/L) for disinfection—and reverse osmosis. Free chlorine concentration was maintained at <0.1 mg/L, and combined chlorine was 1.5–2 mg/L (as chlorine). The RO brines were used locally to grow salt-tolerant plants. The pilot-scale RO unit consisted of 6 pressure vessels containing a total of 18 membrane elements in a two-stage, 2:2:1:1 array (Fig. 1). Membrane elements were 2.5-inch diameter by 40-inch length polyamide thin film composite membranes (ESPA2-2540, Hydranautics and later Koch TFC ULP). RO pressure requirements ranged from 80 to 110 psi, adjusted to maintain constant recovery (80%). The average permeate flux was 0.5 m/day. The feed water temperature varied from 15 to 28 °C.

Two SSF units (north and south) were operated in parallel. The North Slow Sand Filter (NSSF) and the South Slow Sand Filter (SSSF) were filled with silica sand (ES) from OgleBay Norton Industrial Sands, Inc. (Colorado Springs, CO) [26]. Both sands had a d_{10} of 0.34 mm, and uniformity coefficient (d_{60}/d_{10}) of 1.7. Particle size distributions, as determined by sieve analyses, were similar. SSF design parameters were as shown (Table 2). Filtration rates were 1.6, 3.1, 4.7, and 6.3 m/day (0.027, 0.053, 0.080, and 0.107 gal/ft^2/min; 1.7, 3.3, 5.0, and 6.7 million gal/day/acre) during constant flow operation. These values provided a range of operational conditions covering most of the SSF range of operation recommended by the Arizona Department of Environmental Quality—1.9 to 9.4 m/day (0.032 to 0.159 gal/ft^2/min; 2.0 to 10.0 million gal/day/acre) [27]. Excess pretreated water was wasted as necessary to produce a steady RO feed of ~18 L/min.

SSF operations were interrupted for filter cleaning when constant flow operation could no longer be maintained due to filter head loss. At that point, 1.5 cm of sand containing the schmutzdecke was manually removed from the top of the filter. The sand was dried, sieved and subsequently used to re-sand the SSFs. After cleaning, filters were run in

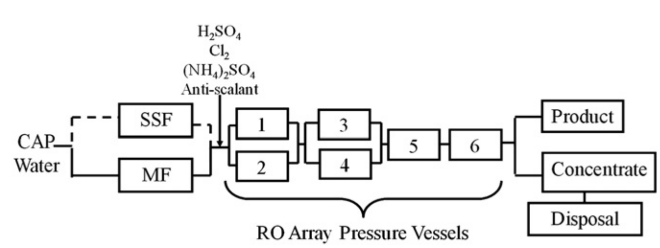

Fig. 1. Schematic of the science and technology pilot-scale desalination facility in Marana, AZ. The pilot scale facility was used to desalinate CAP water from 2007 to 2010.