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A survey of desalinated permeate post-treatment practices

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ABSTRACT

As part of the Water Research Foundation (Denver, CO) project "Post-Treatment Stabilization of Desalinated Water," a questionnaire was developed and distributed to water utilities employing desalination processes to survey post-treatment practices, compile process and water quality data, highlight operating cost and post-treatment operation experiences, and identify distribution system secondary impacts. A total of eighty-three surveys were distributed to water utilities in the United States (USA), Caribbean and Europe, and responses collected over a period of six months duration from the time of initial mailing. Twenty-five questionnaires were returned yielding a thirty percent response rate. Twenty-one of the twenty-five responses were received from the USA, three from Europe and one response was received from the Caribbean. The average-daily permeate flow of the facilities surveyed ranged from 0.39 m^3/min (0.15 million gallons per day (MGD)) to 184 m^3/min (70 MGD). Results indicated a variety of methods are employed when post-treating desalinated permeate, with a majority of the surveyed facilities reporting the use of chemical addition using caustic soda (sodium hydroxide) or soda ash (sodium carbonate) for pH adjustment. More than one form of post-treatment was implemented with or without the need for by-pass or native source water blending, and was dependent on source water type. Facilities that relied upon process by-pass for post-treatment stabilization reported blending ratios between 10 and 30%, with an average blending flow rate between 5.26 m^3/min (2.0 MGD) and 27.6 m^3/min (10.5 MGD). Blended water alkalinity averaged 150 mg/l as $CaCO_3$, as compared to post-treatment with alkalinity adjustment that approximated 62 mg/l as $CaCO_3$ at the point-of-entry (POE). Primary disinfection was typically accomplished by chlorine addition, although a number of facilities reported using chloramines for secondary disinfection. The reported pH averaged 8.2 units at the POE.

Keywords: Survey; Desalination; Synthetic membrane processes; Post-treatment; Seawater; Brackish water; Disinfection; Degasification; Stabilization

1. Introduction

Desalination of sea or brackish water is an important, rapidly growing source of drinking water around the world. Today, reverse osmosis (RO), nanofiltration (NF), and electrodialysis reversal (EDR) are the most commonly used desalination processes for potable water treatment in the United States of America (USA), typically treating brackish or impaired water supplies [1]. It is anticipated that in the future many seawater RO water treatment plants (WTPs) will be constructed in the USA, as many such plants have been operating successfully globally for more than 30 years [2,3]. With a growing number of potable water purveyors turning to desalination processes as a means for augmenting existing drinking water supplies as well as improve water

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quality, it is important to understand the behavior of desalinated permeate within the distribution system and the possible issues that may arise if proper post-treatment of permeate is not practiced. The mineral and organic composition of the water is significantly changed by a synthetic membrane process, which typically requires permeate to be partially reconstituted or treated further to achieve stable finished water that can safely be distributed in pipelines and distribution systems [4–9]. Moreover, desalinated water is considered corrosive due to its inherently low mineral content, and may not be suitable for consumption without adequate post-treatment measures [10].

Although information regarding the application and effectiveness of brackish and seawater desalination to augment drinking water supplies is readily available with regards to pretreatment, process optimization, energy efficiency and concentrate management, less has been documented with regards to post-treatment practices, requirements and secondary impacts. A recent overview of the current state of sixty-two full-scale RO and NF plants conducted for plants greater than 2.63 m^3/min (1.0 MGD) of capacity, used for either seawater desalination, brackish water desalination, or wastewater reclamation provided an insight into post-treatment practices [11]. All of the surveyed facilities reported using at least one post-treatment method for permeate conditioning and corrosion control. Most of the brackish water RO plants responding to the survey reported using degasification-decarbonation and caustic soda addition, with the majority blending permeate with groundwater. Permeate disinfection was reported to be used by 85% of the surveyed facilities that responded, most of which used chlorine. However, whether or not the final composition of the finished water has a positive or negative impact on the viability of distributed water quality or distribution system infrastructure remains for the most part undocumented. Possible issues that may arise after introducing desalinated water into existing distribution systems may include an increase in corrosion and subsequent requirements for control, loss of disinfectant residual, formation of regulated and non-regulated disinfection by-products, hydraulic limitations, infrastructure maintenance, aesthetics, and customer acceptance.

A project funded by the Water Research Foundation (Denver, CO) entitled "Post-Treatment Stabilization of Desalinated Water," explored post-treatment of desalinated permeate streams and provided guidance to water purveyors practicing desalination [12]. One aspect of the research included assessing post-treatment methods practiced by the industry, the effects of these practices on finished water quality and associated impacts within drinking water distribution systems. This was accomplished by surveying several municipal water suppliers that utilize membrane desalination water treatment processes; this paper presents the results of this effort to document information regarding the water community's desalinated permeate post-treatment practices.

2. Questionnaire development and distribution

A questionnaire was developed and distributed to eighty-three water utilities employing desalination processes to gather information regarding post-treatment practices. The surveys were distributed and responses collected over a six month period from the time of mailing. Selected utilities receiving the survey were located in the United States (U.S.), Caribbean, and Europe. The questionnaire was developed using information gathered through a review of relevant literature pertaining to membrane water treatment processes and permeate post-treatment practices. Phone interviews were also conducted with some of the participating utilities to aid in the organization of the questionnaire. The questionnaire requested information on the facility's water quality data, in addition to delineation of post-treatment practices and identification of impacts experienced in the distribution system. Questions were also phrased to obtain information regarding plant descriptions, operation costs, and post-treatment experiences.

Of the eighty-three questionnaires distributed to water utilities a total of twenty-five questionnaires were returned, representing a thirty percent return rate, and their responses used for data analysis. Of the twenty-five utility responses, twenty-one came from the U.S., three from Europe and one from the Caribbean. The specific names of participating utilities have been withheld in order to respect the integrity and security of these utilities, particularly those who reported information regarding operational problems, water quality, or other issues. Consequently, each utility was assigned a number, 1 to 25, to be used for identification and discussion purposes.

3. Results and discussion

3.1. Background information requested in questionnaire

One component of the utility questionnaire requested general information about the desalination facility, including source water and membrane treatment process. Source water and selected membrane process are major factors influencing the choice and sequence of post-treatment operations. Source waters containing higher levels of total dissolved solids (TDS) will require greater pressures for water production, limit process recovery and increase the occurrence of salt passage whereby affecting the mineral content of produced permeate [1,4]. Typical membrane treatment processes include reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF) and electrodialysis reversal (EDR); however, the questionnaire focused on utilities employing RO, NF and EDR technologies. These processes vary in their treatment capabilities, with RO offering more solute removal, as compared with NF and EDR. Therefore, when compared with NF and EDR, RO produced permeate will typically contain the lowest concentrations of dissolved solids, and usually require a greater amount of post-treatment. EDR is an electrically driven process removing only charged particles; thus, uncharged dissolved solids will remain in the desalinated water effecting treated water quality. Hence it is necessary to consider treatment aspects of the membrane process in order to effectively analyze post-treatment options and requirements.

Utilities were also requested to indicate the source of feed water their desalination plant processed using the categories identified in Table 1. The categories were organized according to TDS content and water type that included ocean seawater (SW), brackish groundwater (GW) or surface water (SFW), and GW well, or SFW. Table 2 provides a summary of the reported background information and includes facilities' feed water category as well as the indicated source water, facility type, water quality driver and design recovery. According to questionnaire responses, twelve of the twenty-five utilities indicated that brackish GW was the feed water type supplying their desalination process, six of the plants utilize fresh GW, and three treated SW. Two of the municipalities represented brackish SFW, and two of the respondents, utilities 24 and 25, reported treatment of water sources not listed in the defined categories shown in Table 1. This data supports observations made by others that synthetic membrane processes are not readily employed for treatment of high or low brackish and fresh SFW supplies; rather, RO, NF and EDR use are more commonly used for treatment of GW sources, although their use for seawater treatment is increasing [13].

Table 1
Source water categories by associated TDS content

Category	Feed water category	TDS (mg/l)
1	Seawater	20,000–35,000
2	Brackish Ground Water	1,000–5,000
3	Brackish Surface Water	1,000–2,500
4	Fresh Ground Water	<1,000
5	Fresh Surface Water	<1,000

Another component of the questionnaire was designed to identify the facility type, and to characterize the TDS that was being treated, which was aimed at categorizing utilities according to their water quality goals. The responses have been organized by source water type in Table 2. According to surveyed responses, twenty out of twenty-five plants surveyed used RO membranes, where the remainder of utilities indicated either NF or EDR was used as the membrane process type. Participating utilities were requested to provide information on what specific water quality parameter or combination of water quality parameters drove the decision to implement a desalination process for water treatment. As shown in Table 2, of the twenty-five reporting utilities, eighteen plants listed salinity reduction or salt as the major water quality driver. Hardness removal was identified by sixteen of the respondents as a major water quality driver, whereas six of the facilities listed total organic carbon (TOC) as a major water quality driver. A portion of the respondents reported that some other driver was responsible for the decision to use a desalination process, and none reported the use of the technology for synthetic organic compound (SOC) removal.

3.2. Plant characteristics

One section of the questionnaire requested information from utilities concerning facility hydraulic capacity, membrane process recovery, and permeate water (or desalinated water stream in the case of EDR) end-use. A plant's operating capacity will affect the quantities of chemicals necessary during post-treatment operations, and the volume of produced water will determine the size and number of unit operations utilized during post-treatment. Typically, the recovery of a membrane process is limited by the scaling or fouling potential of the feed water's dissolved solids concentration, in addition to the membrane's pretreatment process and type of membrane material relied upon for treatment.

It is not uncommon to experience a greater degree of salt passage when operating at higher recoveries, and especially when source waters have a greater concentration of dissolved solids. High salt passage increases the mineral content of produced permeate affecting the choice and degree of post-treatment operations necessary to produce stabilized finished water. For example, high salt passage of a feed water containing elevated concentrations of sodium and chloride would be undesirable as these ions in the permeate can affect the taste and overall quality of the finished water. Therefore, an RO membrane would be used in this case, operating at a lower recovery and resulting in a higher rejection of dissolved solids. The permeate water would be significantly depleted in mineral content requiring a

Table 2
Summary of plants' reported background information

Plant number	Feed water category	Source water	Facility type	Water quality driver	Recovery (%)
1	Seawater	Ocean Well	RO	Salt	42
2	Seawater	Gulf/Bay	RO	Salt	55–60
3	Seawater	Ocean Well	RO	Salt	25
4	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	75
5	Low Brackish GW	Brackish Water Well	RO	Salt, hardness, nitrate and manganese	75.5
6	Low Brackish GW	Brackish Water Well	RO	Salt	80–85
7	Low Brackish GW	Brackish Water Well	RO	Hardness	75
8	Low Brackish GW	Fresh Ground Water Well	RO	Salt and fluoride	80
9	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	80
10	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	50
11	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	75
12	Low Brackish GW	Brackish Water Well	RO	Salt, hardness, TOC and radionuclides	75
13	Low Brackish GW	Brackish Water Well	RO	Salt	80
14	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	80
15	Low Brackish GW	Brackish Water Well	RO	Salt and hardness	70
16	Low Brackish SFW	Lake/Reservoir	RO	Salt, hardness and pesticides	82
17	Low Brackish SFW	Lake/Reservoir	EDR	Hardness	28
18	Fresh GW	Fresh Ground Water Well	NF	TOC and color	98
19	Fresh GW	Fresh Ground Water Well	NF	Hardness, TOC and color	80–85
20	Fresh GW	Brackish Water Well/ Mountain Spring	RO	Salt and hardness	75
21	Fresh GW	Fresh Ground Water Well	RO	Salt, hardness, TOC and arsenic	75–80
22	Fresh GW	Fresh Ground Water Well	NF	Hardness, TOC and color	80
23	Fresh GW	Fresh Ground Water Well	NF	Hardness and color	90
24*	Other – Reclaimed Water	Secondary Treated Water	RO	TSS and pathogens	85
25*	Other – Effluent Wastewater	Secondary Treated Water	RO	Salt, TOC and total nitrogen	85

*Reclaimed/secondary treated wastewater used for industrial purposes or GW recharge.

greater degree of post-treatment. On the other hand, a NF membrane may be selected to treat a source water containing appreciable levels of calcium hardness. This membrane allows for a greater degree of salt passage, rejecting fewer ions when compared with an RO membrane. The process often operates at a higher recovery and the produced permeate contains a greater concentration dissolved minerals, which may allow for fewer post-treatment operations to produce a stabilized finished water.

If pressure increases and all other variables are held constant, then the permeate concentration will decrease. If the membrane process recovery is increased, and all other variables are held constant, then the permeate concentration increases. These effects may be hard to realize if an existing membrane array is considered; however, it is difficult in such an environment to increase pressure without increasing recovery. Process operations therefore effect post-treatment considerations because of salt passage impacts due to operating conditions [1,4,14].

Evaluation of responses indicated that 72% of the plants had a design hydraulic capacity between 2.63 m^3/min (1.0 MGD) and 39.4 m^3/min (15 MGD), and were designed for future expansions. Approximately 12% of the respondents had design hydraulic capacities of less than 2.63 m^3/min (1.0 MGD), and 16% were greater than 39.4 m^3/min (15 MGD). Permeate production rates ranged from 0.39 m^3/min (0.15 MGD) to 184 m^3/min (70 MGD) across the respondents. Many of the facilities reporting indicated that a significant amount of flow is blended across the facilities. As indicated in the responses, blending water varied among utilities and included raw or treated GW and SFW. Responses also indicated that some facilities by-passed a portion of filtered raw water for blending purposes. Blending ratio (as a percentage) and its control also was one component of the post-treatment operations survey. The average ratio of blend water to total produced water ranged from 6% to 90%. The lower blend percentages were typically reported by those facilities utilizing a by-pass blend operation. Utilities blending multiple source waters in addition to desalinated water reported higher blend percentages. For example, Plant 2 represents a municipality that produces finished water from a blend of SW, fresh GW and SFW; 90% of the total finished water is represented by the fresh GW and SFW blend and SW represents the remaining 10%. Of the plants that were surveyed, the highest average flow of the blend water flow was approximately 57.8 m^3/min (22 MGD).

Reported feed water recovery values ranged from 25% to 95%, shown in Table 2. Plants showing the highest recovery values included plant numbers 18, 23, 24 and 25, with recoveries of 98%, 90%, 85% and 85%, respectively. According to Table 2, Plant 18 utilized a NF membrane process treating fresh GW. Although a recovery of 98% is not typical for NF processes, the choice of membrane material along with the low TDS concentration of the feed water allowed for a high recovery operation not typical of industry experiences. Both Plants 24 and 25 employed an RO treatment process for secondary treated water while obtaining 85% recovery. Table 2 indicates that Plant 23 employed a NF membrane technology that treated fresh GW. This plant achieved 90% recovery in their process, which is in the typical range of 85% to 90% recovery for NF processes. The majority of plants utilizing low brackish GW as their source water achieved recoveries between 70% and 85%, which is typical for brackish water RO applications.

Plants operating at the lowest recoveries included Plants 1, 3 and 17, with recoveries of 42%, 25% and 28%, respectively. Plants 1 and 3 both utilize an ocean well as their water source. Seawater as a source water typically contains the highest levels of TDS concentration limiting the recovery of the process and requiring the highest transmembrane pressures. Plant 3 reported the lowest recovery of 25%. Several factors contribute to this low value including the age of the plant, membrane element type and material, and highly fouling source water. Plant 17 reported a recovery of 28% and represents a special case as this facility employs an EDR process. In this specific case, EDR was limiting due to the excessive scale-forming materials present and because EDR productivity is limited at higher TDS feed levels due to current density limitations within the EDR stack; RO would have experienced similar recoveries, if not less, due to the presence of sulfate scale as well as high levels of silica.

3.3. End-use characteristics

Intended end-use for desalinated water streams produced from membrane desalination processes will affect the choice and sequence of post-treatment operations. Twenty-three of the twenty-five plants indicated that the produced water was intended for human consumption. Other end-uses include industrial use, groundwater recharge for indirect potable reuse, groundwater recharge as a seawater intrusion barrier, and irrigation. Desalinated water streams produced from some of the participant utilities were intended for multiple uses. For example, the water produced by plant number 19 was used for potable water, industrial use and irrigation; plant 24 produced water only for irrigation and groundwater recharge for indirect potable reuse; and the permeate produced from plant 25 was used to recharge groundwater for indirect potable reuse and as a seawater intrusion barrier. Potable water end-use would require disinfection whereas agricultural or industrial re-use needs would not necessarily require a disinfection post-treatment unit operation. Consequently, the desired end-use of membrane produced water is a significant factor in determining the extent of post-treatment. Finished water intended for human consumption will not only have to conform to regulated health standards for safe drinking water, but will also have to take into consideration secondary standards relating to taste, odor and appearance, all of which affect consumer acceptability. On the other hand, water intended for irrigation purposes will have to be monitored for dissolved salt concentrations and for such items as sodium adsorption ratios and boron, as acceptable levels vary and are dependent upon local agriculture [1,8].

3.4. Post-treatment information

Another section of the questionnaire requested information on post-treatment including post-treatment operations, disinfectant types and residual goals, and problems experienced by the plant as related to post-treatment. Table 3 summarizes findings related to post-treatment operations, associated disinfection practices, corrosion control measures and post-treatment related issues. In comparing chemical versus bypass post-treatment methods, nineteen of the plants reported the use of caustic chemical addition, and twenty-two relied on by-pass or native water blending for stabilization of desalinated permeate.

Utility responses revealed that the choice and sequence of their post-treatment operations varied, therefore establishment of an effective post-treatment process is source water and site specific. This further emphasizes the need to evaluate factors specific to synthetic membrane process, source water and plant location in the design of a post-treatment process. As shown in Table 3, most facilities indicated that blending and/or pH adjustment were included in post-treatment operations. Air stripping or degasification were used for hydrogen sulfide or carbon dioxide removal, and for disinfection chorine or chloramines addition was utilized.

Participant utilities reported that pH adjustment was the most common method for addressing issues related to pH control and establishing some form of corrosion control in the desalinated process stream. Caustic addition in the form of NaOH was the common method identified for pH adjustment. This method is successful in increasing the system pH; however, NaOH addition alone provides only hydroxide alkalinity, and does not address issues related to buffering content. Some utilities reported using caustic addition in the form of Na_2CO_3 or soda ash to control pH. This method would be more advantageous to NaOH addition as it increases the system pH and bicarbonate alkalinity content concurrently, which increases the buffering capacity of the water. Some utilities listed addition of caustic soda along with carbon dioxide for control of pH and increasing the finished water stability. The addition of the carbon dioxide in the caustic environment can shift the carbon dioxide to bicarbonate, thus increasing the bicarbonate alkalinity of the water and likewise the buffering capacity [15].

Many facilities reported utilizing by-pass or native water blending as a portion of their post-treatment design. Blending or by-pass descriptions have also been summarized in Table 3. The blending of permeate for stabilization is common practice for water purveyors utilizing desalination for potable water use. For example, permeate may be blended with finished water from a conventional treatment process or with source water fed around the desalination process via a by-pass stream. The responses indicate that there are a variety of options with regards to blending and by-pass practices, and that the appropriate blending strategy is dependent on the chemical and physical properties of the waters involved.

Most plants used a combination of disinfection practices for post-treatment; however, the most commonly reported disinfection chemicals include free chlorine and chloramines. Regarding primary disinfection, ten of the plants use chlorine, and twelve of the plants implemented chloramines for secondary treatment to serve as the distribution systems' disinfectant residual. The remaining three facilities, plant numbers 16, 24 and 25 reported the use of other disinfectants including chlorine dioxide and ultraviolet (UV) light combined with peroxide (H_2O_2). None of the respondents reported using ozone for chemical disinfection. Goals for free chlorine in the finished water leaving the treatment facilities ranged from 0.5 mg/l to 4.0 mg/l. Pathogen contaminant removal values ranged from 3 to 4 log removal, representing 99.9% to 99.99% reduction of pathogens. Residual goals ranged from 2–4 mg/l as free chlorine.

The reliability of a post-treatment system is important for achieving stabilized water that meets regulatory requirements. Surveyed plants were asked if post-treatment problems or distribution system impacts occurred as a result of the facilities' post-treatment system. The responses have been summarized in Table 3. Common issues noted by those surveyed included biological growth in the degasification/stripping towers, scaling of the degasification/stripping towers and red water events. Failure of an effective post-treatment process may have a significant impact on the water quality within the distribution system. Some of the most common deteriorations in water quality observed by respondents related to disinfection residual stability, red water events, black water events and corrosion in the distribution system.

Table 3
Summary of plant's post-treatment operations, corrosion control measures and related issues

Plant number	Feed water category	Sequence of post treatment operations	Blending or by-pass	Disinfection	Corrosion control	Post treatment or distribution system issues
1	Seawater	1) pH adjustment 2) Air stripping 3) Caustic addition 4) Disinfection 5) Corrosion inhibitor	None	• Primary: chlorine • Secondary: chlorine	• pH adjustment • Corrosion inhibitor	• Fouling/biogrowth in air stripping towers • Chemical injector plugging • Corrosion events
2	Seawater	1) CO2 addition 2) Saturated lime injection 3) Disinfection 4) Blending	Seawater permeate blended with treated SFW, blended product is adjusted for pH and alkalinity, and blends with GW	• Primary: chlorine • Secondary: chloramine	• pH, alkalinity and hardness adjustment facility with CO2 and saturated lime addition • Blending	• Calcium turbidity in finished water.
3	Seawater	1) Air Stripping 2) Decarbonation 3) Disinfection 4) Caustic addition	Permeate is blended with LS water if available	• Primary: chlorine • Secondary: chloramine	• pH adjustment with NaOH • Blending	• None • Plant is for emergency standby and does not run continuously
4	Low Brackish GW	1) pH adjustment 2) Degasification 3) Disinfection 4) Blending 5) Caustic addition	LS GW and IX water blended with RO permeate. RO process operates as a direct ratio to the IX process.	• Primary: chlorine • Secondary: chloramine	• pH adjustment with NaOH • Blending for alkalinity and hardness adjustment	• Chemical injector plugging • Corrosion of plant infrastructure between RO and IX blending location
5	Low Brackish GW	1) By-pass blending 2) Air Stripping 3) Blending with sequestering agent 4) Caustic addition 5) Disinfection	Raw water by-pass blending prior to air stripping. Finished permeate blended with native SFW and aquaduct supplies.	• Primary: chlorine • Secondary: chloramine	• pH adjustment with NaOH • Raw water by-pass blending • Manganese sequesterants	• Corrosion events • Colored or red water • Manganese precipitation; problem addressed by limiting volume of by-pass blend
6	Low Brackish GW	1) By-pass blending 2) pH control 3) Disinfection 4) Corrosion inhibitor	Permeate blended with brackish raw water bypass stream.	• Primary: chlorine • Secondary: chlorine	• Raw water by-pass blending • pH adjustment • Blended phosphate corrosion inhibitor	• Distribution system impacts • Conventionally treated surface water represents primary supply
7	Low Brackish GW	1) pH adjustment 2) Disinfection 3) Blending	Permeate blended with sand filtered GW	• Primary: chlorine • Secondary: chlorine	• pH adjustment with NaOH • Blending with GW for hardness and alkalinity adjustment	• Corrosion events

(Continued)

Table 3 *(Continued)*

Plant number	Feed water category	Sequence of post treatment operations	Blending or by-pass	Disinfection	Corrosion control	Post treatment or distribution system issues
8	Low Brackish GW	1) Air stripping 2) Blending 3) pH adjustment 4) Disinfection	Permeate blended with raw water by-pass stream	• Primary: chlorine • Secondary: chloramines	• pH adjustment with NaOH • Raw water by-pass blending for fluoride addition	• None reported
9	Low Brackish GW	1) Air Stripping 2) Blending 3) Alkalinity recovery 4) Disinfection 5) Corrosion inhibitor	Permeate blended with filtered raw water by-pass stream	• Primary: chlorine • Secondary: chlorine	• Filtered raw water by-pass blending • Alkalinity recovery with CO_2 addition followed by NaOH • Phosphoric acid corrosion inhibitor	• Foulding/biogrowth in air stripping towers • Extensive red water event; problem addressed with alkalinity recovery operation
10		1) By-pass blending 2) CO2 addition 3) Air stripping 4) pH adjustment 5) Disinfection 6) Corrosion inhibitor	Permeate blended with filtered raw water by-pass stream prior to air stripping	• Primary: chlorine • Secondary: chlorine	• Filtered raw water by-pass blending based on TH concentration • Alkalinity recovery with CO_2 addition followed by NaOH • Zinc orthophosphate corrosion inhibitor	• Fouling of air stripping towers (sulfur build up on media and biogrowth) • Turbidity events
11	Low Brackish GW	1) By-pass blending 2) Air stripping 3) pH adjustment 4) Disinfection	Permeate blended with filtered raw water by-pass stream prior to air stripping	• Primary: chlorine • Secondary: chlorine	• Filtered raw water by-pass blending • pH adjustment with Na_2CO_3	• Chemical injector plugging
12	Low Brackish GW	1) Air stripping 2) pH adjustment 3) Blending 4) Disinfection	Permeate blended with IX treated GW that has been degasified	• Primary: chlorine • Secondary: chlorine	• pH adjustment with NaOH • Blended with IX treated GW for alkalinity and TH adjustment	• Scaling of air stripping towers • Fouling/biogrowth in air stripping towers • Chemical injector plugging • DBP formation concerns
13	Low Brackish GW	1) By-pass blending 2) Sequestering agent 3) Air stripping 4) Disinfection 5) pH adjustment	Permeate blended with filtered raw water by-pass stream with added sequesterant prior to air stripping	• Primary: chlorine • Secondary: chloramine	• Filtered raw water by-pass blending with added sequesterant • pH adjustment with NaOH	• Blending limitations • Color • Red water

14	Low Brackish GW	1) Air stripping 2) Blending 3) Corrosion inhibitor 4) Disinfection 5) pH adjustment	Permeate blended with LS and NF treated waters to maintain desired pH and TH	• Primary: chlorine • Secondary: chloramine	• Blending with LS and NF waters for TH adjustment • pH adjustment with NaOH • $(NaPO_3)_6$ corrosion inhibitor	• Scaling of air stripping towers
15	Low Brackish GW	1) By-pass blending 2) Air stripping 3) pH adjustment 4) Disinfection	Permeate blended with filtered raw water by-pass stream prior to air stripping	• Primary: chlorine • Secondary: chlorine	• Filtered raw water by-pass blending • pH adjustment with NaOH	• Red/black water
16	Low Brackish SFW	1) Alkalinity recovery 2) Blending 3) pH adjustment 4) Disinfection	RO permeate is blended with GW supplies.	• Primary: chlorine dioxide • Secondary: chlorine dioxide	• Alkalinity adjustment with CO_2 and NaOH • Blending with treated GW based on TH concentration • pH adjustment - NaOH or CO_2	• Corrosion events related to transport of permeate to GW blending locations • pH stability
17*	Low Brackish SFW	1) pH adjustment 2) Disinfection	None	• Primary: chlorine • Secondary: chloramine	• pH adjustment with NaOH	• Biogrowth in EDR membranes • pH stability • Disinfection residual stability • Biological regrowth
18	Fresh GW	1) Blending 2) Disinfection	Permeate blends with concentrate treated NF permeate and disinfected GW	• Primary: chlorine • Secondary: chloramine	• Blending with additional NF permeate and disinfected GW	• Fouling/biogrowth in air stripping towers • Color • Red water • Disinfection residual stability
19	Fresh GW	1) Degasification 2) Caustic addition 3) Corrosion inhibitor 4) Disinfection 5) Blending	NF permeate blended with native LS GW	• Primary: chlorine • Secondary: chloramine	• pH adjustment • Orthophosphate corrosion inhibitor • Blending with native LS GW	• pH stability • Red/black water • LCR violation due to use of lower quality corrosion inhibitor; strict specification procedures now enforced.
20	Fresh GW	1) Air stripping 2) pH adjustment 3) Blending 4) Disinfection	Permeate blended with GAC filtered water	• Primary: chlorine • Secondary: chlorine	• pH adjustment with NaOH • Blending with GAC filtered water	• None reported

(Continued)

Table 3 *(Continued)*

Plant number	Feed water category	Sequence of post treatment operations	Blending or by-pass	Disinfection	Corrosion control	Post treatment or distribution system issues
21	Fresh GW	1) By-pass blending 2) pH adjustment 3) Corrosion inhibitor 4) Disinfection	Permeate blended with filtered raw water by-pass stream	• Primary: chlorine • Secondary: chloramine	• Filtered raw water by-pass blending • pH adjustment with NaOH • Polyphosphate corrosion inhibitor	• Blending limitations due to arsenic • Red/black water events
22	Fresh GW	1) Air stripping 2) pH adjustment 3) Disinfection	None	• Primary: chlorine • Secondary: chlorine	• pH adjustment with NaOH	• Disinfection residual stability
23	Fresh GW	1) Air stripping 2) Blending 3) Corrosion inhibitor 4) Disinfection 5) pH adjustment	Permeate blended with LS and RO treated waters to maintain desired pH and TH	• Primary: chlorine • Secondary: chloramine	• Blending with LS and NF waters for TH adjustment • pH adjustment with NaOH • $(NaPO_3)_6$ corrosion inhibitor	• Scaling of air stripping towers
24†	Other – Reclaimed Water	1) Degasification 2) Decarbonation 3) Lime addition	Decarbonated permeate is blended with a portion of the permeate that by-passes the decarbonation operation	• Non potable: UV with H_2O_2	• Permeate blended with decarbonated permeate • pH, alkalinity and hardness adjustment with lime addition	• Formaldehyde formation • Disinfection residual stability • Biological regrowth • Clogging of injection wells due to excess lime dosages
25†	Other – Effluent Wastewater	1) Degasification 2) Decarbonation 3) Partial blending 4) Lime addition	Decarbonated permeate is blended with a portion of the permeate that by-passes the decarbonation operation	• Non potable: UV with H_2O_2	• Permeate blended with decarbonated permeate • pH, alkalinity and hardness adjustment with lime addition	• Carryover of lime particulate causing increased final product turbidity • Increased fouling of injection wells for seawater intrusion barrier; addressed by modifying lime injection system

NR: Not reported; GW: Groundwater; LS GW: Lime-softened groundwater; IX: Ion exchange; LCR: Lead and copper rule; SFW: surface water; SF: Sand filter; GAC: Granular activated carbon; TH: total hardness; FW: freshwater; LCR: Lead and Copper Rule; DBP: disinfection by-product; $(NaPO_3)_6$: sodium hexametaphosphate; UV: ultraviolet; H_2O_2: hydrogen peroxide
*EDR plant.
†Reclaimed/secondary treated wastewater.

Table 3 summarizes utility's reported methods of corrosion control. All of the surveyed facilities indicated that some form of pH adjustment was used as their method for corrosion control; and blending was also indicated by twenty-three utilities. Alkalinity adjustment and corrosion inhibitor addition were also cited as corrosion control measures. Most plants did incorporate two or more methods for corrosion control in their facility. The use of corrosion inhibitors has increased since the passage of the Lead and Copper Rule requirements of the safe drinking water act (SDWA). Recent studies document the effectiveness of inhibitors for corrosion control on blends of desalinated seawater with treated surface water and ground water supplies [16,17,18]. The most prominent forms of inhibitors reported to be used are polyphosphates, zinc phosphates, and silicates. Operating data provided by the participant utilities indicated that the choice of inhibitor depends upon pH, alkalinity, calcium and total hardness, chloride, sulfide, iron, and dissolved oxygen levels of the source water. At least one participant utility reported the improper selection of a corrosion inhibitor that did not effectively condition the water, which eventually led to that particular water purveyor falling out of compliance with the provisions of the SDWA Lead and Copper Rule action levels. Selection of a different inhibitor formulation was required for this utility to regain compliance.

3.5. Post-treatment water quality

A portion of the questionnaire was designed to collect water quality information as related to membrane process post-treatment applications. Water quality parameters of interest in the survey included general water quality parameters, metals, and microbiological parameters. The membrane facilities were requested to provide water quality information regarding RO permeate, blend water, and the POE to the distribution system. Low, high, and average parameter values were requested to be provided by each respondent. A majority of the plants responding reported average values, which have been used in subsequent data analysis. For those facilities that did not report average values, the data reported as the high value or the available data were relied upon for data analysis.

Fig. 1 presents a plot of average alkalinity for desalinated permeate, blend and POE water. Alkalinity is identified and discussed as this water quality parameter is commonly referred to when assessing the chemical stability of water intended for distribution for human consumption. Additionally, research has shown that maintaining an alkalinity concentration above 80 mg/l as $CaCO_3$ is the one of the most important individual parameters for preventing release of metal ions to the water [19,20]. The alkalinity of the blend water is appreciably different than the permeate and POE data that was reviewed. This is most likely because the blend water is derived either from the raw water source or from another source that contains appreciable levels of alkalinity. Use of blend water to increase the alkalinity of the permeate water prior to distribution at the POE is typical for corrosion control and stabilization purposes. As a result, alkalinity is typically higher for the blend water, which averaged approximately 142 mg/l as $CaCO_3$. Alkalinity at the POE averaged at least one milli-equivalent per liter (meq/l), or 60 mg/l as $CaCO_3$, which is an important consideration for post-treatment stability. The dataset appears to agree with industry trends that target between one and two meq/l of alkalinity as $CaCO_3$ in order to provide sufficient buffering for the distribution system [1,20].

Fig. 2 summarizes the reported average turbidity for the permeate, blend, and POE water sample locations. The data indicates that the turbidity, although low for permeate, is actually lowest as identified at the point of entry, which would not be unexpected, particularly if other water plants feed the same POE. In addition, turbidity of desalinated plants at the reporting locations is not significantly different when reported as averages, so it is shown that, as would be expected, permeate produces high quality water with respect to turbidity.

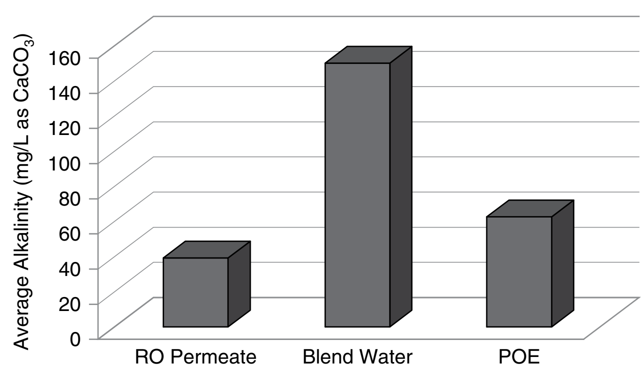

Fig. 1. Average alkalinity for permeate, blend and point of entry.

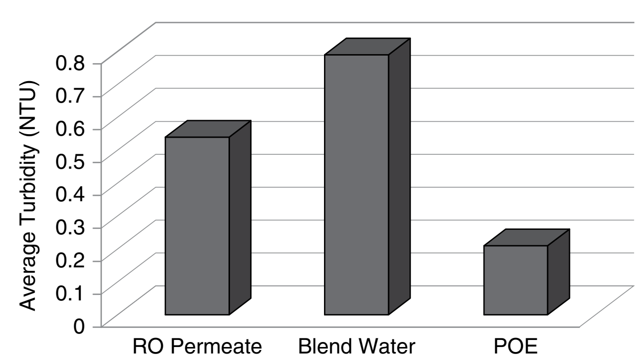

Fig. 2. Average turbidity for permeate, blend and point of entry.

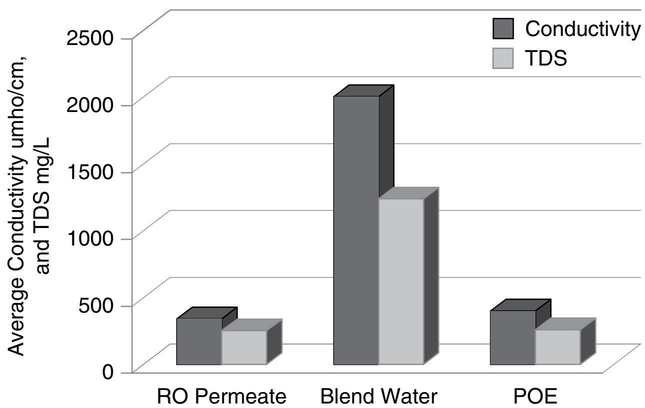

Fig. 3. Average conductivity and TDS for permeate, blend and point of entry.

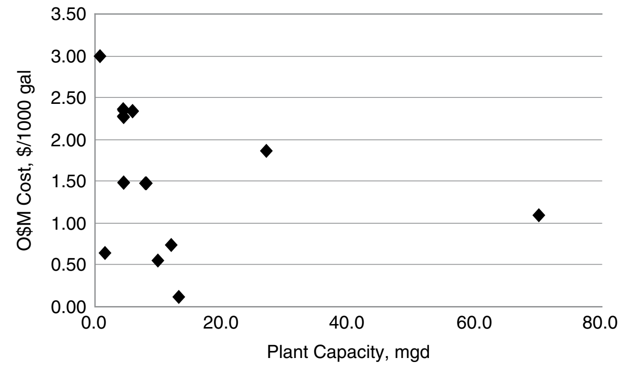

Fig. 4. Operation and maintenance cost versus plant capacity.

Fig. 3 is a plot of the average conductivity and TDS for the permeate, blend, and POE sample locations. Note that TDS and conductivity are related; however, specific correlations should not be used because the data presented are averages across many different types of water supplies. The permeate TDS is reported as below the secondary standard of 500 mg/l, one of the goals of most desalination facilities. Conductivity and TDS are greater than the secondary water quality standard in the blended water supply, which is not unreasonable since many plants by-pass the native raw water supply to blend with permeate to economically add stability. The blended water and/or treated water prior to distribution (at the POE) will meet the secondary standard of 500 mg/l, which is reflected in this data being reported.

Water quality parameters that were not consistently provided by the respondents in returned questionnaires included hydrogen sulfide, silica, bromide, algae, heterotrophic plate count bacteria, and the Langelier and Ryznar indices. These parameters (or indices) may not typically be collected by water process and plant personnel, and the questionnaire confirmed that many of these parameters are only collected for use in special studies or other non-traditional membrane process operation protocols. Although the Langelier and Ryznar indices are often referred to when evaluating corrosivity of drinking water, the use of these indices may not be uniformly practiced for process control as is evident by the results of the questionnaire.

3.6. Post-treatment O&M costs

Operation and maintenance (O&M) costs were collected from each plant and were categorized by plant capacity, labor, chemicals, energy, membrane replacement, replacement parts and concentrate disposal. Fig. 4 presents a graph of plant capacity versus operation and maintenance cost. According to Fig. 4, a strong correlation is not shown between plant capacity and costs, which may indicate that other O&M costs were not provided or shown; however, it is more likely that total O&M costs are provided rather than the post-treatment O&M costs only. Since it is not possible to extract the different costs from that data presented, the information presented in this section should be reviewed with this understanding. It is typical that there is an economy of scale that would be expected for this type of evaluation. Moreover, O&M costs for this evaluation were difficult to analyze because of the various and inconsistent methods the facilities presented their data. For example, O&M costs from a European facility were reported in euro and had to be converted to dollars, using an average rate at the time the data was provided and may not represent changing interest or other impacts on costs over time; a conversion on $1.4132 dollars per euro was used for this calculation.

Fig. 5 is a graph showing plant average O&M cost for labor, chemicals, energy, membrane replacement, replacement parts and concentrate disposal. As expected, the data indicates that labor, chemical and energy costs

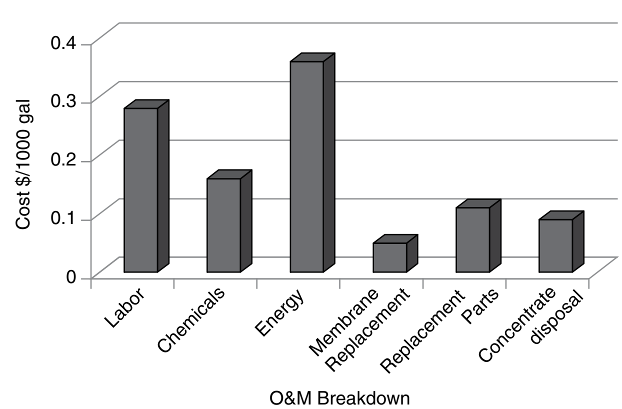

Fig. 5. Operation and maintenance cost breakdown by cost category.

are the largest contributors to O&M costs. Energy costs remained relatively consistent for the facilities that did report data; however, one plant reported a significantly higher energy cost, which may reflect contracted rates or could be due to the small plant size reported.

3.7. Lessons learned

This last section of the survey questionnaire requested respondents to cite details on any identified major issues that their facility experienced regarding post-treatment. In addition, respondents were requested to share any of their lessons learned as a result of operating their membrane facility. Respondents were asked to reveal if pilot test showed any water quality concerns for the distribution system. Twelve of the respondents reported used pilot testing for membrane process evaluations prior to implementing their desalination, however, they did not necessarily include specific post-treatment pilot components. Eleven of the responders considered the impact of permeate on the drinking water distribution system, which supported the observation that few water authorities pilot both the membrane process and distribution system together.

A number of facilities surveyed noted that failure to incorporate post-treatment considerations into planning and design functions would result in negative post-treatment impacts. Water purveyors that did incorporate post-treatment considerations into planning and design functions reported fewer problems. For example, one facility reported problems after plant start up with clogging of concentrate injection wells, as well as distribution system impacts due to sulfur residuals. In this case, the utility identified that its failure to properly evaluate post-treatment impacts created additional issues that impacted cost. As such, it is important to stress the need to have an effective design that takes into account post-treatment stabilization of permeate.

Permitting and meeting regulations are other important aspects of implementing and operating a desalination facility. The survey included a question to determine what obstacles had to be overcome with regards to post-treatment permitting. Three of the utilities responding to the survey reported that they experienced permitting and regulation issues. Ten participants did not respond to the question and the remaining reported that they had not experienced any significant permitting issues.

Participants surveyed were asked to give details about the issues experienced in the distribution system upon plant startup and how the identified issues were resolved. As shown in Fig. 6, forty percent of the plants reported having no significant issues; however, thirty percent reported that they had experienced issues related to manganese precipitation and color caused by bypassing feed water at higher than desirable blending volumes, which was resolved by modifying plant operation by the addition of a sequestering chemical, addition of bypass stream greensand filters, and the reduction of blend ratios. One utility response indicated that temperature was one parameter not fully vetted when exploring membrane processes, as warmer water from deep source wells had negative impact on customer acceptance when used. This situation was resolved by intentional blending of the warmer water supplies with an alternative source water having cooler temperatures. Some of the participants reported undefined corrosion issues with premise plumbing, which was resolved with the use of corrosion control chemical.

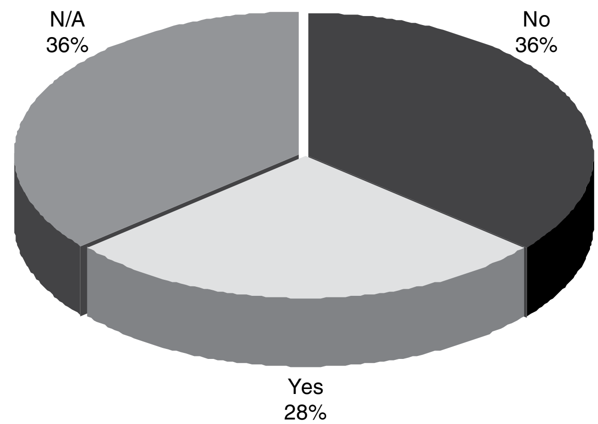

Fig. 6. Have the distribution system issues been directly related to post-treatment?

Seven of the respondents reported issues with operations related to post-treatment facilities. Nine did not respond and the remaining reported as not having significant operational issues. Operational issues that were identified included inadequate control of disinfection when using chloramines, and red water issues, which were resolved by the addition of a combination of carbonic acid and sodium hydroxide to increase alkalinity in the distributed finished water.

4. Summary of findings

A utility questionnaire was developed and distributed to utilities known to rely on desalination processes and located in the U.S., Caribbean, and Europe to gather information on post-treatment. Water quality data was obtained from each facility, in addition to delineation of post-treatment practices and identification of impacts experienced in the distribution system. Questions were also asked regarding plant descriptions, operation costs, and post-treatment actual experiences. Post-treatment was found to consist of several different unit operations for RO and NF membrane systems, and are summarized in Table 3.

Compilation and analysis of the questionnaire results indicated that there are a variety of methods currently relied upon that could be used for post-treatment of permeate. A majority of the surveyed facilities reported the use of degasification, air stripping, chemical addition of caustic soda for pH adjustment, with or without the need for by-pass or native source water blending. In some instances, more than one form of post-treatment was implemented. Many facilities reported taking advantage of blending and by-pass options for post-treatment stabilization purposes; however, specific methods or types of sources use widely varied between utilities. Treated ground and surface waters were reported to be used to accomplish blending for some facilities. These native waters were treated with a variety of methods including ion exchange and lime softening. Some blending descriptions included by-passing of the raw feed water. Of the facilities that reported degasification and blending for post-treatment, few reported blending issues or biological growth within degasification units. Primary disinfection is accomplished mainly by chlorine addition, although a number of facilities reported using chloramines for primary treatment. These results are in agreement with previously reported post-treatment unit operations for potable water supplies reliant upon brackish ground water [5,9]. Reported post-treatment operations for desalinated seawater were also in agreement with previously reported treatment operations [8,15].

The survey conducted in this project provided information about facilities' finished water quality, which was used to calculate average values of alkalinity and pH. Blended water alkalinity averaged about 150 mg/l as $CaCO_3$, as compared to post-treatment using alkalinity adjustment, which averaged approximately 62 mg/l as $CaCO_3$ at the POE. In addition, the average pH was 8.2 at the POE, along with an average daily permeate flow ranging from 0.39 m^3/min (0.15 MGD) to 184 m^3/min (70 MGD) and an average blending flow rate ranging from 5.26 m^3/min (2.0 MGD) and 27.6 m^3/min (10.5 MGD). Chloramine disinfectant was the main chemical used for secondary disinfection to carry residual into the system. Chlorine residual goals reported by the surveyed facilities ranged from 2–5 mg/l at the point of entry (i.e. leaving the plant), and 1.0 mg/l within the distribution system. Facilities reporting the use of chloramines indicated that residual goals of 4.0 mg/l leaving the plant is desired and was between 1.0 mg/l and 2.5 mg/l within the distribution system.

5. Recommendations offered by surveyed utilities

Based on the lessons learned information obtained from the post-treatment questionnaire, membrane process practitioners provided several recommended actions for utilities considering post-treatment processes of desalinated process streams. The questionnaire findings clearly indicated that more than one form of post-treatment was required, that could include bypass blending operations. Facilities that were reliant upon using by-pass recommended establishing bypass or blending ratios based on multiple water quality parameters, and not simply by salinity or TDS levels. It was recognized that water purveyors needed to consider determining the disinfection by-product formation potential and disinfection residual impacts of the blend or bypass water source on the final blend, which could be more limiting than salinity or TDS alone. Blended water alkalinity was recommended to fall between 50 and 125 mg/l as $CaCO_3$, for seawater facilities, and between 75 and 150 mg/l as $CaCO_3$ for brackish water facilities. Of the facilities that reported degasification and blending for post-treatment, it was recommended that the degasification towers be designed with cleaning processes to control biological growth within the degasification units. Also, if monochloramine was to be used for residual (secondary) disinfection, then at least 2.5 mg/l of a combined chlorine residual was recommended as a minimum target to combat the onset of nitrification events within the distribution system.

One comment that was also consistently provided by the reporting utilities that had experienced distribution system related problems when using desalinated process streams was that pilot testing of the membrane process in concert with identified post-treatment options was recommended. Although the participant utilities conducted process pilot studies prior to construction activities, none conducted post-treatment studies as part of their initial study efforts. By considering post-treatment processes when piloting membrane processes, the participant utilities believed that the efforts would be useful to identify secondary post-treatment water quality effects, and in doing so, limit possible adverse post-treatment impacts on the distribution system. Pilot testing can help determine issues related to such items as stabilization, degasification, disinfection, corrosion control, and blending concerns. A combined or comprehensive approach to permeate post-treatment design evaluations was seen to be beneficial because the proper design of the post-treatment processes will reduce impacts within the facility, particularly blending practices.

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