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Post-Treatment Stabilization of Desalinated Water

Subject Area: Water Quality

Post-Treatment Stabilization of Desalinated Water

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The Water Research Foundation (formerly Awwa Research Foundation or AwwaRF) is a member-supported, international, 501(c)3 nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

The Foundation's mission is to advance the science of water to improve the quality of life. To achieve this mission, the Foundation sponsors studies on all aspects of drinking water, including resources, treatment, distribution, and health effects. Funding for research is provided primarily by subscription payments from close to 1,000 water utilities, consulting firms, and manufacturers in North America and abroad. Additional funding comes from collaborative partnerships with other national and international organizations and the U.S. federal government, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated.

From its headquarters in Denver, Colorado, the Foundation's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

The results of research are disseminated through a number of channels, including reports, the Web site, Webcasts, conferences, and periodicals.

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More information about the Foundation and how to become a subscriber is available on the Web at **www.WaterResearchFoundation.org**.

Post-Treatment Stabilization of Desalinated Water

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FOREWORD

The Water Research Foundation (Foundation) is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The Foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the Foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The Foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the Foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The Foundation's trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

SUMMARY

Desalination of sea or brackish water is an important, rapidly growing source of drinking water around the world. The mineral composition of the water is significantly changed and then partially reconstituted to achieve stable finished water that can be distributed in pipes. Whether or not the ultimate composition of the finished water has a positive or negative impact on the viability of distribution system components, distributed water quality, and health of long-term consumers of desalinated water supplies remains for the most part unknown.

With a growing number of potable water purveyors turning to desalination processes as a means for augmenting existing drinking water supplies, it is important to understand the behavior of desalted permeate within the distribution system and possible issues that may arise if proper post-treatment of permeate is not practiced. Desalination water is considered corrosive due to its inherently low mineral content and is not suitable for consumption without post-treatment.

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 and hence is available with regards to post-treatment requirements and secondary impacts. The behavior of desalinated water in the distribution system remains largely non-documented, and potential issues that may arise after introducing desalinated water into existing distribution systems include impacts on internal corrosion control, disinfectants and disinfection by-products, hydraulics, infrastructure maintenance, aesthetics, and customer acceptance.

The research project was conducted to reveal lessons learned, survey the industry practice, and develop concepts and guidelines for the post-treatment stabilization of membrane permeate. The work also to highlighted existing information gaps and identified associated research needs.

POST-TREATMENT

Post-Treatment Is Required

Pure water is considered a reactive chemical. Water that contains little to no hardness would be considered unhealthy for potable use and is often found to be aggressive towards distribution system components. In addition, drinking water that contains no dissolved oxygen may be offensive and taste flat. Consequently, post-treatment of membrane desalinated water is required prior to storage and distribution for municipal water purveyors, and must include disinfection.

Table ES.1 presents the typical categorization of permeate post-treatment depending on source water type. There are four primary issues concerning the post-treatment water. These relate to blending, remineralization, disinfection and the materials used for storage and transport of the water to the tap. Desalinated water is often blended with other sources that contribute minerals to the final blended water. Seawater as a source for blending is limited due to issues related to corrosivity and taste if the blending levels exceed about 1%. Blending of permeate water with seawater results in the addition of sodium, potassium, calcium, and magnesium to drinking-water but also will contribute bromide and iodide which are DBP precursors. Consideration should be given

Table ES.1
Typical post-treatment processes based on supply type

Supply type	Process	Examples of applicable post-treatment processes
Seawater	RO	1. Recarbonation. 2. Lime addition. 3. Calcite bed filtration. 4. pH and/or alkalinity adjustment. 5. Addition of corrosion inhibitors. 6. Primary and secondary disinfection. 7. Blending with fresh water supplies.
Brackish water (surface)	RO, NF, EDR	1. pH and/or alkalinity adjustment. 2. Addition of corrosion inhibitors. 3. Primary and secondary disinfection. 4. Blending with fresh water supplies.
Brackish water (ground)	RO, NF, EDR	1. Decarbonation (degasification) 2. Hydrogen sulfide stripping. 3. pH and/or alkalinity adjustment. 4. Addition of corrosion inhibitors. 5. Primary and secondary disinfection. 6. Blending with fresh water supplies. 7. Bypass blending with raw water supply.
Fresh water (ground)	NF, EDR	1. Decarbonation 2. Hydrogen sulfide stripping. 3. pH and/or alkalinity adjustment. 4. Addition of corrosion inhibitors. 5. Primary and secondary disinfection. 6. Blending with fresh water supplies. 7. Bypass blending with raw water supply.

to the natural minerals present and whether these will result in finished water having unacceptable water qualities in addition to unacceptable taste and odor.

Membranes do not remove small, uncharged molecular contaminants or dissolved gases such as carbon dioxide, hydrogen sulfide and methane. If hydrogen sulfide is present in a source groundwater, it must be removed, typically by packed tower or air stripping processes prior to disinfection and distribution to consumers. If gaseous sulfides are removed in the stripping process, then provisions are also made to remove (scrub) the off-gas sulfides from the air stripping tower to prevent odor and external corrosion issues on surrounding buildings and infrastructure. The stripping of carbon dioxide and hydrogen sulfide raises the pH and reduces the amount of base needed to perform stabilization. Permeate is typically low in calcium, magnesium, alkalinity and may have a low pH if acid was used for pretreatment ahead of the membrane process. Since the permeate is corrosive to downstream piping and appurtenances, alkalinity and pH adjustments are accomplished with bases such as sodium hydroxide, and inhibitors may also be employed for corrosion control purposes.

There is also an issue regarding potential anthropogenic pollutants from a range of sources which need to be considered on a local basis taking into account potential pollution sources and threats. This is the case whenever any external and potentially minimally treated water source is used for blending. Disinfection and filtration of the blending water will be necessary if there is any possibility of microbiological or other regulated parameter contamination, in which case similar considerations regarding the formation of by-products in the blending water apply. Generally the natural organic matter or TOC content in finished water is very low and the yield of by-products from final disinfection would be expected to be low as a consequence (McGuire Environmental 2004). However, blending with other source waters can prove to be problematic for desalted permeate, should bromide be present, or should the blend not provide enough buffering to the desalted permeate resulting in an unstable finished water.

Chemicals and Post-Treatment Issues

Post-treatment may be achieved by the addition of chemicals as described in the literature. If this is undertaken there are three primary concerns that need to be addressed:

a. The quality of the additives and the introduction of chemical contaminants produced during the manufacture, storage, distribution and transport. Unlike pre-treatment chemicals, there are no downstream processes that will remove undesirable contaminants.
b. Controlling dose rates so that required concentrations are provided. This can prove difficult when dealing with permeate that contains little to no buffering capacity downstream of a membrane process, as without buffering rapid pH changes can occur with minimal dose of acid or base chemical.
c. Preventing or minimizing unwanted chemical reactions following chemical addition. This issue is similar to blending. Localized changes can occur at dosing points leading to fouling problems on a micro-scale, particularly when by-pass or blending is considered.

Brackish and Seawater Post-Treatment Methods

Post-treatment of the permeate water from the desalination processes can include several unit operations, each dependent upon the source water type and desalination method. Considerations of post-treatment, based on literature findings, include:

- Stabilization by addition of caustic hydroxide alkalinity is the most widely used approach for brackish desalinated permeate in order to provide corrosion control for metallic pipelines and distribution systems, although this method is often accompanied by the addition of corrosion control inhibitors. Stabilization can also be achieved by carbonate alkalinity adjustment, remineralization by blending with source water(s) and the use of caustic soda-carbon dioxide or calcite bed contactors have been reported.
- The enhanced removal of specific compounds (i.e., boron, silica, NDMA, etc.) is site specific and source dependent.
- Sodium hypochlorite and chlorine gas are most widely used for disinfection of desalinated water. However, the use of chloramines instead of chlorine for residual disinfection is more advantageous when product water must be conveyed over long distances (over 100 km), or when stored for long periods of time (several days) due to the significantly lower decay rate of chloramines compared to free chlorine.

- Use of ozone as a disinfectant for desalinated water is limited as this practice has the potential of forming bromate as a disinfection by-product.
- Blending of desalinated water for remineralization is suitable with brackish water, but only feasible to up to about 1% with seawater. The raw water used for blending should be pretreated for chemical and microbial control prior to mixing with the desalinated water.

The primary desalination water plant post-treatment unit operations for potable water supplies reliant upon brackish groundwater are the following (AWWA 2007; Duranceau, 1993):

- Carbon dioxide removal (degasification or decarbonation);
- Hydrogen sulfide removal (stripping) and odor control treatment (scrubbing);
- Alkalinity recovery, pH adjustment, stabilization and corrosion control; and,
- Disinfection.

Alternative treatments reported for use in seawater desalination post-treatment applications include (Withers 2005):

- Addition of carbon dioxide and excess lime;
- Filtration of carbon dioxide dosed permeate through limestone bed contactors;
- Application of sodium carbonate and hydrated lime;
- Application of sodium bicarbonate and calcium sulfate;
- Application of sodium bicarbonate and calcium chloride;
- Blending with a native low-salinity water source or by-pass blending.

Remineralization can be categorized into a series of four treatment processes: (1) chemical addition without lime or limestone; (2) carbon dioxide addition followed by limestone bed contactors for dolomitic dissolution, (3) carbonic acid addition followed by lime dosing; (4) blending with water containing high mineral content.

CONCLUSIONS

Literature Review Findings

A review of relevant literature indicated that post-treatment is required for desalted permeate, and would include consideration of possible impacts from blending, remineralization, disinfection, storage and distribution. Stabilizing permeate water is accomplished by effectively controlling aspects of post-treatment. Most of the literature pointed to the use of various chemical treatments to achieve post-treatment goals. Literature indicates that there are several considerations that should be taken into account when deciding post-treatment strategies, including the quality of the chemicals added, controlling dosage rates, and minimizing unwanted chemical reactions within the distribution system. It was found that primary post-treatment unit operations includes degasification (decarbonation) for CO_2 removal, air stripping for H_2S removal, alkalinity and pH adjustment for stabilization, corrosion control, and disinfection. Post-treatment unit operation performance is dependent on the source water type and the desalination process. Stabilization of finished water can typically be accomplished through the addition of carbonate alkalinity, the use of corrosion inhibitors, remineralization through blending with source water, disinfection, and enhanced removal of specific compounds.

Due to low mineral content of desalted water, blending with source water allows for the addition of mineral such as sodium, calcium, potassium, and magnesium. When seawater is used for blending, the ability to by-pass source water and blend permeate for stability is limited to one percent, and hence is not typically practiced. In addition, it has been reported that blending could be problematic if bromides are present because of the possible formation of regulated and non-regulated DBPs, and possible impacts of bromide on chloramines disinfection.

Effective disinfection of desalted water is accomplished by the use of sodium hypochlorite, chlorine gas, chloramines, and ozone. It is important to note that disinfection-by-product formation of blended finished water supplies could be greater when blending native source waters containing TOC with seawater permeate due to higher concentration of bromide in the permeate. Recently iodinated DBPs have gained more attention as evidence suggests their presence in many water supplies across the US; however, the relative contribution of seawater permeate to iodinated DBP formation due to the passage of iodide across the membrane remains in question. Stabilization and disinfection are required components of post-treatment processes.

Questionnaire Findings

Based on the information obtained from the literature review, 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.

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 (sodium hydroxide) 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. Treated ground and surface water were reported to be used to accomplish blending for some facilities. Specific details on blending were provided by some facilities who reported blending with ion exchange treated source water, by-passed raw groundwater, and lime-softened or calcite filtered groundwater.. 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.

Chloramines 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 mg/L within the distribution system. Facilities reporting the use of chloramines indicated that residual goals of 4 mg/L leaving the plant is desired and was between 1 mg/L and 2.5 mg/L within the distribution system.

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. Blending options included: (1) blending permeate with raw by pass water, (2) blending using water from lime softening, RO and NF processes, (3) blending with brackish water or water produced by ion exchange. Facilities that were reliant upon using by-pass reported bypass blending ratios between ten and thirty percent. The survey conducted in this project provided information about facility's 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 0.15 MGD to 70 MGD and an average blending flow rate ranging from 2 to10.5 MGD.

One comment that was consistently provided by the reporting utilities that had experienced distribution system related problems when using permeate as part or all of their water portfolio was that pilot testing of the membrane process in concert with the post-treatment would be useful in identifying possible issues and aid to limit adverse impacts. Pilot testing can help determine issues related to such items as stabilization, degasification, disinfection, corrosion control, and blending concerns. Most facilities did not incorporate pilot post-treatment testing, yet did acknowledge they performed pilot testing for the membrane process. 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.

Lessons Learned—Expert Workshop Proves Beneficial

A workshop was conducted that brought together experts in the field of desalination where they could describe their experiences with post-treatment stabilization, share lessons they have learned, and offer guidance to utilities experiencing problems with post-treatment. The experts identified fourteen priority guidance recommendations to deal with the many issues associated with post-treatment, as were presented in Table 4.2.

The expert workshop was a positive and well-executed activity where fourteen priority issues were identified. The highest ranked priority was related to how utilities should approach post-treatment stabilization with regards to help and available information. The main idea behind this highest priority is that stabilization of permeate water is a mandatory component of post-treatment for desalination facilities. Utilities should explore and define consistency goals by evaluating how much variation their systems can withstand without experiencing problems in the distribution system, since there is a range of variability that a distribution system can tolerate when integrating desalinated water into an existing water distribution system.

The second highest-ranked priority dealt with permeate conditioning and corrosion control. This topic is interrelated to the highest priority topic identified in the workshop. NF and RO permeate are considered corrosive to many types of materials of construction. Permeate produced by synthetic membrane processes can be "aggressive" water that if not stabilized may cause internal damage to many of the components that make up the water distribution system. The utility is required to understand the interrelated issues between treatment and the distribution system with respect to regulatory compliance, distribution integrity, and reliability, and the premise plumbing impacts specifically related to lead and copper release at consumer taps.

The third highest priority pertains to the challenges of disinfection by products formation during and following post-treatment operations. Considerations must be made with regard to the type of disinfection(s) used and there potential for DBP formation, whether it be chlorinated chloraminated, brominated, or iodated species. With regards to pretreatment, the use of pH buffers must be taken into account when it comes to their impact on post-treatment. DBP precursors in bypass water must be considered as a contributor to the total DBP concentration in the distribution system, while providing for inactivation of pathogens. Seasonal changes as well as mixing different water sources in the distribution systems should be identified.

Other priorities were related to defining water quality goals that are assessed based on source water type. Since blending is commonly used to improve stability of permeate water, caution was offered by the workshop participants based on their experiences because there can be secondary impacts of blending in the distribution system with regards to consumer confidence and water quality; hence, planning and testing should be taking into consideration when blending. Additional priorities were related to classification of the source of blending to achieve finished water quality goals. Consumer acceptance is imperative, so educating the public on the regulations related to desalinated water and post-treatment is necessary. Pretreatment can affect post-treatment decisions and careful selection on unit processes and chemical addition should be considered prior to use.

Questions Resolved by the Research

The objective of this study was to review membrane post-treatment case studies, conduct expert workshops to report practical experiences, denote lessons learned, identify research gaps, and suggest desalinated water post-treatment guidelines relative to water quality. The research was intended to supply answers to a number of questions asked by water purveyors considering, or actively engaged in, the use and application of desalination. The following answers to the questions considered in the research are offered in hopes of providing benefit to the drinking water community:

- Water quality—What water quality parameters need to be identified as potential issues specific to desalinated waters as compared to more traditional sources?

  To stabilize permeate water and prevent corrosion (metal release) of piping systems and domestic plumbing, post-treatment is necessary to return some calcium hardness and bicarbonate alkalinity to the water. In many situations, post-treatment also includes the removal of carbon dioxide to raise the pH, hydrogen sulfide removal when required, and the addition of fluoride which is removed during the desalting process. Corrosion control is a priority when either directly pumping desalted finished waters into the distribution system or when blending different water sources from membrane process. The constituents of concern when establishing a post-treatment process strategy include pH which will be dependent upon the buffering capacity and bicarbonate alkalinity, temperature, calcium, sulfate, chloride, dissolved oxygen, boron, total dissolved solids concentration (conductivity) and corrosion indices. These parameters are interrelated in the final treatment process selected for post-treatment, depending on application and source water.
- Corrosion indices—What types of indices are useful? Are new indices needed to provide better estimates of useful life of pipe materials?

  Several indices have been developed to indicate the stability or corrosivity of potable water. Although no single index is definitive, and some may at times be misleading, potable water corrosiveness or scaling potential can be evaluated and determined with a combination of indices. Each index provides information on the nature of the potable water; however, many of the indexes found in the water treatment and corrosion control literature are only approximations. The most common corrosion index in use is the Langelier Saturation Index (LSI). However, the buffer intensity (β), calcium carbonate precipitation potential (CCPP), Casil index, Larson ratio, and Ryzner index are also typically considered. There is need for the development of a "post-treatment" index that is specific to synthetic membrane processes that considers both corrosivity impacts and disinfection impacts in a combined format or procedure. Many of the participant utilities identified the need for developing this concept in a computer "tool" format. Additional discussion is provided in the research needs section of this report.

- Corrosion control—What are the most economical methods for providing corrosion control? What impacts are there associated with permeate pH adjustment on alkalinity recovery and disinfection by-product formation?

  Many of the plants surveyed indicated that two or more methods for corrosion control had been incorporated into their design in dealing with post-treatment: pH adjustment was the most common economical method to be employed for permeate post-treatment. Blending of permeate with mineral-rich source water, either using source by-pass streams or via the blending of permeate with conventionally-treated native (non-saline) source water is a second popular economical method for corrosion control, as indicated in the case studies presented in Chapter 6. Another method often cited for use in permeate corrosion control is the addition of chemical inhibitor.

  - Blending: What criteria should be used for determining blend ratios of different water supplies? Can blending be accomplished in the distribution system or will storage, detention and mixing be required?

    Blending can improve the stability of the permeate streams by increasing the alkalinity and calcium content to reduce the corrosiveness of the desalinated water. The water to be used for blending may be the sources water for the RO process or from another source, and is limited to brackish waters having moderate to low TDS and no significant DBP precursor content. And although blending of desalinated water for remineralization is suitable with brackish water, no more than 1 percent of seawater can be relied upon for blending. Use of bypass blending or reliance on multiple source waters for blending will reduce the overall stress on the membrane system as it reduces the amount of water that needs to be treated and thereby reduces the operation costs on the system. Blended waters from coastal and estuarine areas may be more susceptible to contamination with petroleum hydrocarbons or algal toxins, which could give rise to taste and odor problems. It is necessary to study the effects of different blends to prevent secondary impacts within the distribution system. Should multiple sources be used, the utility should consider the need to develop a unidirectional flushing program or distribution system rehabilitation (including replacement) prior to the incorporation of a desalting process into existing infrastructure. In addition, the water purveyor may also need to increase storage reservoir size to be able to control the blending location of multiple source waters. In most cases, the water purveyor should expect to see an increase in its operational and maintenance expenses. The raw water used for blending should be pretreated for chemical and microbial control prior to mixing with the desalinated water.

  - Inhibitors: What, if any, are the secondary impacts associated with the use of corrosion inhibitors in permeate streams?

    Inhibitors have found wide spread use as a method of corrosion control and are often cited for use in permeate corrosion control; however, there were reported concerns about the secondary impacts that could occur if inhibitors were used as a process chemical. The most prominent forms of inhibitors used are polyphosphates, zinc phosphates, and silicates. These inhibitors control corrosion by several mechanisms, including sequestering of corrosion by-products (such as lead and copper, scale inhibition, development of a coating film on the pipe walls and buffering the water at the desired pH). Operating data indicate that the choice of inhibitor depends upon pH, alkalinity, calcium and total hardness, chloride, sulfide, iron concentrations, 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.

- Post-treatment Unit Operations—Are there certain issues to be aware of when employing specific unit operations for post-treatment applications? What constraints are involved on different post-treatment unit operations with regards to operability, reliability, aesthetics and environmental secondary impacts? Is there significant bacterial regrowth during distribution especially in warm/hot climates?

  Post-treatment processes typically include stabilization, disinfection and corrosion control, and can include degasification and/or air stripping processes if carbon dioxide and hydrogen sulfide gases are present in the permeate water. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies. The choice and sequence of post-treatment operations are typically determined by regulatory requirements, the design of the system, finished water quality criteria and water chemistry. The need for post-treatment generally depends on a number of factors, which includes chemical and microbiological safety, palatability and customer acceptability, and secondary impacts on wastewater influent. Microbial growth would be lower in a water system distributed solely with desalted, stabilized permeate, as in the case of the participating utility, Consolidated Water as there are no nutrients nor appropriate sustainable food source. However, other systems that blend native water supplies with desalinated seawater supplies may contend with microbial issues that impact distributed water quality. Groundwater typically contains higher levels of gaseous hydrogen sulfide, and because the membrane will not remove the hydrogen sulfide, post-treatment for odor control is required where packed towers are in operation.

- Pipe Loop Testing—Is pipe loop testing needed, and if so, what general guidance has been generated for pipe loop testing (i.e., pipe materials, flow conditions, size of pipe)? Are there better measures of corrosion than the use of coupons?

  Although pilot studies are often conducted for membrane process design that includes operational considerations with respect to pretreatment and source viability (i.e., fouling concerns), these pilot studies often do not include adequate consideration of post-treatment processes focused on specific distribution system related issues that are unique to that system. There are on the other hand a number of examples of corrosion control pilot scale (pipe loop) studies that have been conducted over the years, in part or entirely, for compliance with the SDWA's LCR. Corrosion control evaluations are typicallynecessary to evaluate the impacts of treatment changes on corrosivity of internal pipe and distribution system components, and include the evaluation of secondary impacts of identified treatment strategies. Pipe loop tests can incorporate other features of post-treatment with the goal of simulating one or more processes. For purposes of post-treatment evaluations, pipeloop testing racks shouldbe designed to include metal coupons of known weight and materials. Additional techniques that could be used in conjuction with coupons are linear polarization probes, resistance probes and electrochemical noise measurement techniques to integrate concepts related to crevice and pitting corrosion, not simply generalized plumbosolvency methods (i.e., Coupons). A number of techniques can be used and will depend on the scope and depth of the study, but consideration of related topics should be included in the design; for example, disinfection and residual maintenance; DBP formation; lead and copper corrosion inhibitor or pH adjustment tests, and bacteriological regrowth (coliform) evaluations could be integrated into a pilot investigation. Post-treatment corrosivity and stability studies are beneficial in providing information on chemical treatment selection and dosage amounts for post-treatment operations. This has been demonstrated as described in Chapter 6, case studies. Each of the utilities that implemented studies developed beneficial information although each individual study conducted differed in scope Hence, it is important to recognize that multiple sources of corrosivity data is required to fully evaluate this interdisciplinary subject matter, and pipe loops aid in these efforts.

- Disinfection—Can disinfection of permeate water impact other water supplies when introduced into a common distribution system? How does bromide concentration in the permeate impact disinfection by product formation potential if blended into a common water distribution system? Does bromide have an impact on residual stability?

  Disinfection is a required component of post-treatment, and the work presented herein indicated that chlorine and chloramines are the more common disinfection processes use to disinfect permeate streams. The EPA maximum residual disinfectant level (MRDL) of 4.0 mg/L disinfectant residual limits public exposure to chlorine in drinking water systems on a running annual average. Water systems practicing intentional chloramination will dose less than 1 mg/L of ammonia-N chemical to remain below the MRDL residual and avoid excess free ammonia. Without the proper ratio between chlorine dosage rate and ammonia addition (5:1 part Cl_2:NH_3-N) the formation of unstable combined residual will occur. Yet the choice of monochloramine in seawater permeate may not be an effective strategy due to the effect of permeate bromide content on monochloramine residual. Participant utilities expressed concerns with regards to disinfectant stability in seawater permeate and DBP formation in permeate blends of bypass or blend supplies. It has been documented that bromidecan impact residual stability and serve as a source for brominated DBPs. Because blending is a common option for cost effective permeate stabilization, evaluation of the blend or bypass streams with regards to water quality and DBP formation potential is also required. Those systems that practiced chloraminaton as with other systems reliant upon monochloramine residual for secondary disinfection residual requirements rely on distribution flushing as the primary strategy for controlling nitrification. Benefits of flushing are residual restoration, removal of microorganisms and DBPs, at the expense of labor costs, water loss and ammonia formation due to autocatalytic decay of the monochloramine residual itself.

- Taste Testing and Consumer Confidence–Public Acceptability—What problems, if any, may arise with regards to the public's acceptability? Should taste tests be conducted when establishing criteria for post-treatment?

  Most of the surveyed water utilities identified taste and odor as a major worry with respect to customer acceptance and consumer confidence. Although regulated as Secondary Contaminants per the SDWA, taste and odor of permeate is for the most part subjective. Taste refers only to sensations typically referred to as bitter, salty, sour and sweet, and is dependant upon the chemical substances present. Odor, like taste, depends on the chemical substances present in the water being consumed. Certain inorganic salts can produce tastes without odor, and as a result, permeate of desalinated water systems can appear to have a flat taste. If disinfectant is present, a perceived odor can also be noted. Customers have been known to register complaints to their water purveyor when a drastic change in water quality occurs, but given time will become accustomed to a new water quality, assuming no substantial changes to the variability of that quality. Stabilization will reduce the perceived reactions to desalted permeate, in addition to providing its primary associated benefit related to addressing internal corrosion control concerns. Taste tests could be conducted to establish some level of subjective criteria for post-treatment; however, corrosion control test rack studies are recommended as more effective study methods. Prior studies had indicated that the consumer prefers a blended water supply as desalted seawater permeate for drinking water; that is, the water needs to be stabilized else the consumer will object in some manner.

RECOMMENDATIONS

Based on the results of this study, stabilization and effective disinfection of permeate water is the most import aspect of post-treatment design and operation. It is recommended that water purveyors carefully assess the integration of desalination into their water portfolio, and in doing so, develop practical and reasonable post-treatment goals in addition to the goals typically developed for the desalination process itself.

Water Quality Goals for Post-Treatment Processes

The discussions provided herein this literature review indicate clearly that stabilization and disinfection are fundamentally important in the proper design and operation of post-treatment processes. It is therefore important to develop treatment goals and condition that can be used as a guide for developing post-treatment concepts. Although the development of these goals is site specific to the desalination source water and membrane process utilized in treatment, based on the results of this study including literature, survey and case study reviews, it is recommended that the goals presented in Table ES.2 be considered for desalination post-treatment processes (AWWA 2007; Lahav and Birnhack 2007; Duranceau 2001; Applegate 1986; Hasson and Bendrihem 2006;

Table ES.2
Desalination post-treatment water goals for POE

Parameter	Seawater	Brackish water
pH	6.5–9.5	7.5–8.4
Alkalinity (mg/L as $CaCO_3$)	50–125	75–150
Hardness (mg/L as $CaCO_3$)	50–85	75–110
Calcium concentration (mg/L)	50–75	60–100
TDS (mg/L)	100–500	85–350
Sulfate to chloride ratio	1–1.3	0.5–1
Turbidity (NTU)	0.6–3	0.2–2
Boron	0.5–1	NA

Withers 2005; Delion, Mauguin and Corsin 2004; Shi and Taylor 2005; Taylor et al. 2005; Marangou and Savvides 2001; Yermiyahu et al. 2007).

It should be noted that the TDS content should be similar to other supplies when consecutive distribution systems are impacted by the inclusion of a desalination process into a water community's treatment portfolio. The goals in Table ES.2 are presented for use by municipal and/or other water purveyor entities whose primary function is to produce drinking water for consumption while meeting fire demand. Consideration of a stabilized and disinfected permeate (and its blends) SAR value should be taken into account when other water quality criteria are needed due to irrigation or vegetation concerns. An example of this is the o consideration of permeate boron when seawater supplies are to be used in a system that includes irrigation as an end-use.

Recommended Post-Treatment Process Piloting Necessary for Design

The need to stabilize water so that it would not enhance metal corrosion and concrete dissociation has been recognized for decades. Permeate typically is adjusted chemically in order to prevent corrosion of pipes in the distribution network, pH value and carbon dioxide content for scaling prevention. As an example, a buffer intensity greater than 0.5 milliequivalents per pH unit is indicative of a balanced, stabilized source water; to accomplish this the finished water must have adequate alkalinity that may fall within a range of values that are largely dependent on source water treatment and blend water operations. Alkalinity recovery needs to be considered when selecting scaling control options, and depends on how much carbon dioxide and bicarbonate is in the raw water. Regardless, permeate water will require chemical disinfection. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies (Lovins et al. 2004b; Duranceau and Lovins 2005). Although pilot studies are often conducted for RO and NF process design considerations related to pretreatment and process optimization and operation considerations, these pilot studies do not include adequate consideration of post-treatment processes focused on specific distribution system related issues that are specific to the system incorporating the membrane process. It is recommended that water purveyors mandate studies to evaluate the secondary impact of permeate post-treatment (or lack thereof) on water quality and subsequent compliance related topics: disinfection and residual maintenance, the formation of disinfection by-products, maintenance of lead and copper corrosion control, bacteriological regrowth and coliform impacts.

Consequently, pilot plant testing that takes into account post-treatment processes is important to develop proper design to achieve overall drinking water goals for the distribution system. Most water purveyors understand the need to focus on pilot testing for the membrane process, however, as a result of this study that included an expert workshop, pilot testing should extend to include post-treatment processes that are to be implemented for the specific need. This could include such unit operations as degasification, air stripping, pH adjustment or chemical conditioning with bases or inhibitors, and must at a minimum require disinfection evaluations. Considerations for effective post-treatment should also include and understanding of feed water sources, address the potential of by-pass or native water blending for stabilizing permeate, the effect of alternative disinfectants when used (such as chloramines), and a realization to include programs to enhance and evaluate consumer confidence in these efforts.

Research Needs Identified in Second Expert Workshop

Another central phase of this research project was to conduct a workshop involving the participating utilities to identify research needs to address utilities' issues with post-treatment, and in doing so identify research 'gaps' in order to develop a listing of research needs. The workshop was a two-day event, held in southern California, beginning February 9 and ending February 10, 2009. The first day of the workshop was held at the Irvine Ranch Water District's (IRWD's) headquarters in Irvine, California. Representatives from the participating utilities began research needs workshop by answering the question, "In your opinion, what are the three most important post-treatment research needs today?" This discussion led to the development of nine key topics identifying the specific research needs for post-treatment. Table ES.3 presents the results of this effort.

Table ES.3
Identification of research needs

Research need	Issue	Possible outcome(s)	Impacts if not addressed
Chloramine residual stability in permeate water	• Bromides and iodides degrade chloramine disinfectant	• Better analytical methods for iodide and bromide • Improved technologies for removal of bromide and iodide • Increase understanding of bromide and iodide chemistry	• Reduced or eliminate disinfectant residual • Reduces ability to augment existing water sources that use chloramine disinfection
Formation of brominated and iodinated disinfection by products in desalted permeate and its blends	• Potential formation of brominated and iodated DBPs and their unknown health risks • Taste and odor caused by iodated DBPs	• Study effects of blending permeate with traditional water sources • Identifying conditions under which formation occurs specific to blended water	• Future non-compliance with possible regulations made to control current unregulated DBPs • Impacts on public health
Testing protocol for post-treatment of desalinated waters	• The need for testing protocols addressing possible post-treatment operations as permeate water quality is unique to each utility	• Gather information from major desalination plants specifically on water quality before and after introduction of new water sources • Compile existing case studies	• Decreased water quality • Damage to existing infrastructure • Decreased customer confidence • Higher replacement costs • Higher maintenance costs
Evaluation of the impact of seawater permeate post-treatment on existing infrastructure	• Distribution systems are different in materials used for construction and agel the introduction of new, blened water sources may have negative impacts on infrastructure due to water quality changing	• Evaluate changes in corrosivity of blended water sources • Develop guidelines for newer alternative materials of construction that are more compatible with blended water sources • Removal of incompatible materials	• Damage to infrastructure • Decreased water quality • Decreased customer confidence • High maintenance costs
Performance of corrosion-inhibitors or other stabilization chemicals	• Questions remain regarding effectiveness and performance of corrosion inhibitors	• Evaluation of current testing procedures for effectiveness of inhibitors • Develop predictive tool to assess manufacturer's claims regarding effectiveness of their product • Development of coating films for internal pipe surfaces	• Unforeseen damage to distribution system
Studying the effects of blending desalinated seawater permeates with ground and surface water sources on aesthetics and customer satisfaction	• Permeate water is aesthetically undesirable to consumers, however, permeate water is necessary to augment existing water sources, thus proper blending ratios of different waters as yet to be determined	• Pilot or bench scale studies that research various blending ratios • Identify specific constituents that affect taste and odor in blended supplies • Conducting public surveys to evaluate customer acceptance	• Decreased customer confidence
Software tool development for risk analysis in permeate blending with traditional ground and surface water sources	• Seasonal and site specific variations in water quality occur for permeate water and blended water, as such, a software tool is necessary that can adjust for these differences and assess the impact to the water community	• Site visits to appropriate utilities to gather information on infrastructure, materials, and treatment processes • Gather information on unique water quality • Develop a model that combines and relates all factors	• Adverse impacts on water quality • Unforeseen changes in permeate water and blended water • Decreased customer confidence
Identifying specific constituents in and possible reactions present from the blending of permeates from groundwater sources and permeates from swro permeates	• Little is known on possible reactions that may occur from blending different permeate sources	• Water quality assessment specific to permeate water • Bench of pilot scale studies specific to permeate water blends that test various blening scenarios	• Possible decreased water quality • Distribution system damage • Customer dissatisfaction
Identification of alternative post-treatment methods for removal of hydrogen sulfide	• Conventional treatment, nor membrane treatment will remove hydrogen sulfide from water • Existing removal technologies are costly, and labor and maintenance intensive	• Gather all information on existing technologies, especially those other than scrubbers • Possibly adjust or combine existing treatment methods to develop removal technology compatible with desalination treatment	• Hydrogen sulfide is can be corrosive and lead to distribution system damage • Taste and odor issues

CHAPTER 1
INTRODUCTION

MOTIVATION FOR THE PROJECT

Desalination Process Streams Require Post-Treatment

Desalination is intended for the removal of TDS that generally cannot be removed by conventional treatment processes alone. RO, NF and EDR synthetic membrane processes produce process water that requires post-treatment before delivery to the distribution system as finished water. RO and NF synthetic membrane processes in particular produce permeate water depleted in minerals and often is found to be aggressive towards distribution system components; similarly, EDR produces water depleted in ionic content which can result in similar concerns. Different RO and NF membranes may have different mass transfer characteristics; using a membrane with a lower molecular weight cutoff would decrease the permeate concentration. Regarding EDR processes, the amount of electricity imparted to the stack will impact the amount of salt depleted from the processed water stream. Desalination will result in the production of water having low dissolved solids content that is considered corrosive, and may be incompatible with many components and appurtenances that comprise water distribution system infrastructure, such as metallic and concrete appurtenances. The most common post-treatment methods include pH adjustment, disinfection, degasification to remove hydrogen sulfide (if present), and methods designed to reduce corrosiveness (stabilization and corrosion control).

It has been recognized for decades that there existed a need to stabilize permeate to prevent metal corrosion and concrete dissociation. 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 and hence is available with regards to post-treatment requirements and secondary impacts. Consequently, the behavior of desalinated water in the distribution system remains largely undocumented, and potential issues that may arise after introducing desalinated water into existing distribution systems include impacts on internal corrosion control, disinfectants and disinfection by-products, hydraulics, infrastructure maintenance, water quality, aesthetics, and customer acceptance. The research reported herein is intended to provide the drinking water community with information regarding post-treatment stabilization of desalinated water.

Desalination for Drinking Water Production

Water desalination had initially been used to produce or augment drinking water supplies through the use of evaporative or distillation methods. The process is believed to date back to the 4th century BC when Greek sailors used an evaporative process to desalinate seawater. Desalination had initially been used to produce or augment drinking water supplies worldwide via the use of evaporative or distillation methods. Beginning in the 1970s however, the water industry began to focus on commercially viable desalination applications using synthetic membranes. Significant advances in membrane technologies have improved the cost effectiveness and performance capabilities of the membrane. RO membrane processes are increasingly being used worldwide to solve a variety of water treatment problems.

Today, RO, NF, and EDR are the most commonly used desalting processes for potable water treatment in the United States, typically treating brackish or impaired water supplies. Globally, many seawater RO water treatment plants (WTPs) have been operating successfully for more than 30 years (Redondo 2001. Busch and Mickols 2004). Potable water producers continue to rely on membrane processes to augment existing unit operations and improve water quality to allow greater reliance on source waters of relatively poor initial water quality.

Growth of Synthetic Membrane Processes

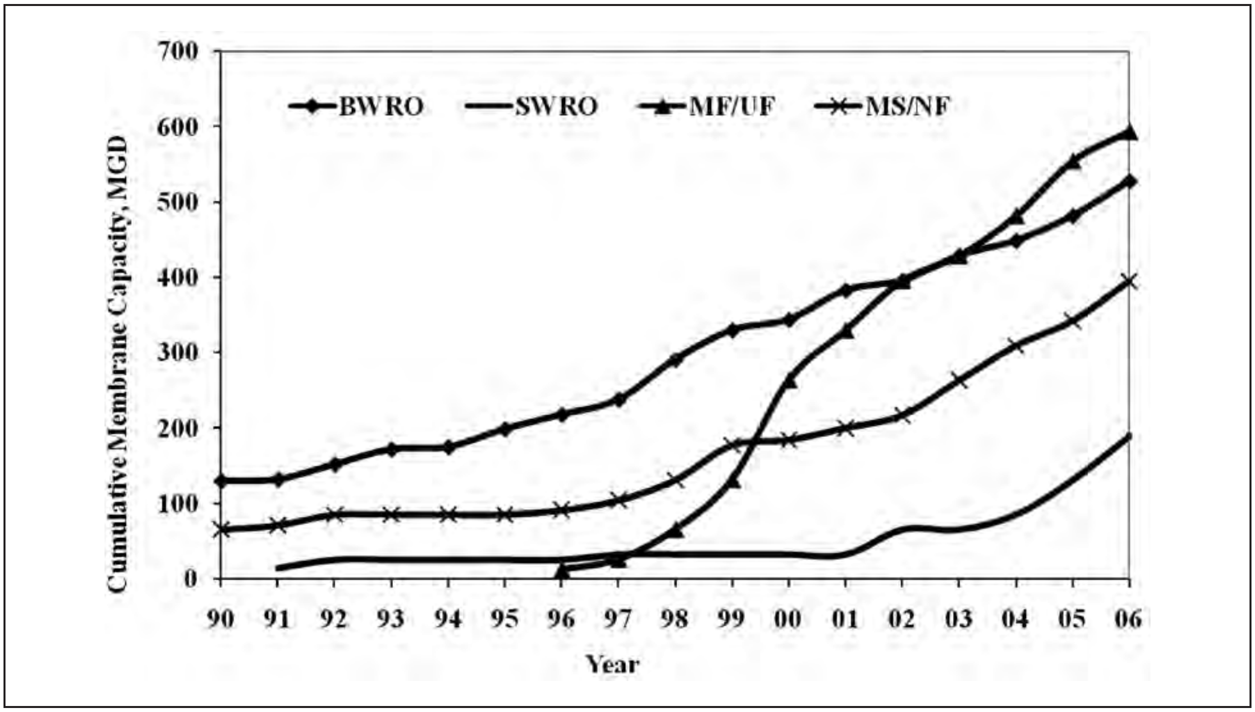
Desalination is an important and rapidly growing source of drinking water around the world originating from sea water or brackish water. Figure 1.1 presents the global cumulative contracted membrane process capacity over time, and indicates that installed desalination capacity has maintained a compounded growth rate of about seventeen percent since 1990 (Global Water Intelligence 2008). Brackish water membrane use has steadily increased, with an accompanying increase in seawater capacity in more recent years. Between 1994 and 2004, world desalination capacity increased from 17.3 to 35.6 million m^3/day (Wannick 2004).

Microfiltration (MF) and ultrafiltration (UF) processes, which are not the subject of this project, have experienced the greatest growth this past decade. It can been seen that the use of synthetic membrane processes for desalination and production of drinking water has increased over the past five decades; this growth has primarily been in coastal areas with limited freshwater sources although inland desalting facilities have been placed into operation more recently. Desalting techniques are primarily intended for the removal of TDS that generally cannot be removed by conventional treatment processes.

The use of synthetic membrane processes for desalination and production of drinking water has increased over the past five decades primarily in coastal areas with limited freshwater sources. Since the development of synthetic asymmetric membranes in 1960, interest in membrane processes, particularly RO and NF for water and wastewater treatment has increased primarily because of the following (Mallevialle et al., 1996):

1. Increased regulatory pressure to provide better treatment for both potable and waste waters;
2. Increased demand for water, especially during times of drought, requiring exploitation of water resources of poorer initial water quality than those relied upon previously; and,
3. Technological improvements have lowered costs associated with the manufacturing and operational use of membrane technologies.

At present time, desalting plants worldwide have the capacity to produce over 6.0 billion gallons a day, which is enough water to provide over 20 gallons a day for every person in the United States (Wangick 2004). About 1,200 desalting plants are in operation nationwide. Most plants operating in the United States are used for either moderately brackish groundwater treatment, for softening and natural organic matter (disinfection by-product precursors) removal, or to produce highly purified water for industrial use. The RO process can remove more than 99 percent of all dissolved minerals and more than 95 percent of organic compounds, as well as biological and



Source: Pankratz; Global Water Intelligence.

Figure 1.1 Cumulative contracted desalination capacity

colloidal suspended matter, including turbidity, from water. NF, also referred to as membrane softening, is used primarily for water softening and disinfection by-product precursor (dissolved natural organic carbon) removal, and can remove up to ninety-five percent of TDS from source water. EDR is employed for lower salinity waters, especially for surface waters having high fouling content or groundwater having high silica content. EDR does not remove microorganisms or small suspended materials from source waters (Taylor et al. 1989).

RESEARCH APPROACH

Objectives

The Water Research Foundation funded this study to survey industry practices and to provide concepts and guidelines for post-treatment stabilization of membrane permeate, present membrane post-treatment case studies, conduct expert workshops, denote lessons learned, identify research gaps, and develop desalinated water post-treatment guidelines linking water quality targets to distribution system operational goals. Consideration to customer acceptance of desalinated water was also reviewed, with key tasks including:

- Review U.S. and international case studies,
- Conduct expert workshops,
- Denote lessons learned,
- Identify research gaps, and
- Present desalinated water post-treatment guidance (best practices).

Approach

The research project was segmented into four major activities:

1. Literature review and web search
2. Distribute, collect, compile and review desalting questionnaires
3. Organization of expert workshops
4. Develop guidelines for membrane permeate post-treatment and stabilization

The research project was conducted as a series of several activities. The first activity consisted of a literature review and web search to collect information on critical issues and document items related to desalination post-treatment, water quality control, and distribution system considerations. The second activity was to convene expert workshops with participants representing U.S. and international water purveyors with experience in the operation of desalination having demonstrated experience in post-treatment processes. The final major activity was to develop concepts and guidelines for the post-treatment stabilization of membrane permeate and highlight existing information gaps to identify associated research needs.

Questions Considered in the Research

The research is intended to assist water purveyors that are considering or implementing the use of desalination, or those wanting to enhance existing operations and facilities, would benefit from being provided answers to the following questions:

- Water quality—What water quality parameters need to be identified as potential issues specific to desalinated waters as compared to more traditional sources?
- Corrosion indices—What types of indices are useful? Are new indices needed to provide better estimates of useful life of pipe materials? Are there better measures of corrosion than the use of coupons?
- Corrosion control—What are the most economical methods for providing corrosion control? What impacts are there associated with permeate pH adjustment on alkalinity recovery and disinfection by-product formation?
  - Blending: What criteria should be used for determining blend ratios of different water supplies? Can blending be accomplished in the distribution system or will storage, detention and mixing be required?
  - Inhibitors: What, if any, are the secondary impacts associated with the use of corrosion inhibitors in permeate streams?
- Post-treatment Unit Operations—Are there certain issues to be aware of when employing specific unit operations for post-treatment applications? What constraints are involved on different post-treatment unit operations with regards to operability, reliability, aesthetics and environmental secondary impacts? Is there significant bacterial regrowth during distribution especially in warm/hot climates?
- Pipe Loop Testing—Is pipe loop testing needed, and if so, what general guidance has been generated for pipe loop testing (i.e., pipe materials, flow conditions, size of pipe)?

- Disinfection—Can disinfection of permeate water impact other water supplies when introduced into a common distribution system? How does bromide concentration in the permeate impact disinfection by product formation potential if blended into a common water distribution system? Does bromide have an impact on residual stability?
- Taste Testing and Consumer Confidence–Public Acceptability—What problems, if any, may arise with regards to the public's acceptability? Should taste tests be conducted when establishing criteria for post-treatment?

CHAPTER 2
LITERATURE REVIEW SUMMARY

EXISTING INFORMATION

Permeate water from a desalination process is characterized as being low in mineral content, containing little to no hardness and alkalinity, and may be aggressive towards treatment and distribution system components. As a result, post-treatment of membrane desalinated water is required prior to storage and distribution and must include disinfection. Post-treatment may be defined as treatment processes that occur downstream of synthetic membrane processes (RO, NF and EDR). Post-treatment processes typically include permeate conditioning for pH adjustment, corrosion control, degasification and disinfection. The treatment processes selected and the order in which they are performed is dependent upon source water type and membrane facility design. Whether or not the ultimate composition of the post treated water has a positive or negative impact on the viability of distribution system components, distributed water quality, and health of long-term consumers of desalinated water supplies remains for the most part unexplored.

An abundance of literature exists for explaining the methods and types of synthetic membrane processes, the resulting water quality of permeate produced from membrane desalination, and types of post-treatment systems that may be used to stabilize membrane permeate water. Appendix A presents a formal and traditional written literature review discussing in detail reference citations regarding membrane process post-treatment practices and water quality considerations. Due to the extensive nature of the literature review, it was apparent that the information needed to be sifted, sorted, organized and compiled in order to condense the information into key summary tables. This chapter provides a tabulated summary of key literature findings identified and discussed in Appendix A. It is in the intent of this chapter to provide a concise summary of the key literature that was used in developing guidance recommendations for this project.

APPLICABLE LITERATURE OVERVIEW AND SUMMARY

Categorization of Source Water

A review of the literature would indicate that post-treatment should be categorized according to the following source waters:

1. Surface water
    - Seawater (SW)
    - Brackish surface water (BSW)
2. Ground water
    - Brackish groundwater (BGW)
    - Fresh groundwater (FGW)

The information is presented as a series of four tables, each representing the respective source water. Table 2.1 summarizes key literature findings for post-treatment of desalinated seawater. Table 2.2 presents a summary of literature pertaining to post-treatment of brackish surface waters.

Table 2.1
Seawater post-treatment summary list by post-treatment process

Post-treatment process	Literature findings	Literature citation
Recarbonation	• Recarbonation is defined as the introduction of bicarbonate and carbonate alkalinity • Addition of carbon dioxide with excess hydrated lime can be used to add alkalinity and make permeate non-aggressive and/or non-corrosive as these chemicals react to form calcium bicarbonate • Aggressive water can be treated using recarbonation to obtain a slightly positive LSI (one that will deposit calcium carbonate) in order to produce a protective scale of calcium carbonate in pipelines conveying the water • Chemical recarbonation contributes to remineralization; however is more expensive than utilizing a high salinity source for blending	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	• Treatments using CO_2 require local availability of the chemical. Storage of this gas requires a refrigerated tank, which can be rented from the gas supplier. • CO_2 can contribute to remineralization of water by bicarbonate formation	Delion, N., et al. (2004) *Desalination*, 165: 323–334.
Lime addition	• Aggressive water can be treated using lime addition to obtain a slightly positive LSI (one that will deposit calcium carbonate) in order to produce a protective scale of calcium carbonate in pipelines conveying the water • Addition of carbon dioxide with excess hydrated lime can be used to add alkalinity and make permeate non-aggressive and/or non-corrosive as these chemicals react to form calcium bicarbonate • Lime treatments typically require 15–35% more CO_2 than equivalent treatment utilizing limestone beds. • Addition of hydrated lime and sodium carbonate tends to produce a non-adherent $CaCO_3$ deposit. This method is more appropriate to natural waters.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	• Lime dissolution by carbon dioxide provides two essential ingredients to the water—bicarbonate alkalinity and calcium content. This process requires proper preparation of and dosing of lime slurries. In this process, typically the reaction goes to completion, thus little excess CO_2 concentration remains.	Hasson, D. and O. Bendrihem (2006) *Desalination*, 190 (1-3): 189–200
	• Post-treatment stabilization can be provided by adding chemical combinations such as carbon dioxide or calcium chloride and sodium hydroxide. These systems can suffer from residual turbidity, maintenance problems, and high operational costs, or they can add unwanted chlorides to the finished water.	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
	• It is necessary to make water slightly scale forming to create a protective deposit on internal surfaces of pipes and equipment. For that purpose, the LSI should be over zero and close to 0.2 ($SI > 1$, $SI \approx 1.2$) • Chemical injection using sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$), calcium chloride ($CaCl$), lime ($Ca(OH)_2$) and CO_2 can accomplish remineralization and a calcocarbonic balance (calcium carbonate equilibrated water). Several treatment options and combinations of these chemicals can be used. Whichever treatment is selected, an LSI goal of 0.2 ($SI = 1.2$) should be desired. Treatment combinations include (Cl_2 is shown for disinfection): 1. $CO_2 + Ca(OH)_2 + Cl_2$: gives a slightly scale forming water ($LSI = 0.2$) without exceeding guidelines for chlorides and sodium. Alkalinity can be increased to an appropriate value using this method. 2. $CaCl_2 + NaHCO_3 + Cl_2$: this method increases sodium and chloride concentrations. Calcium hardness increase will be limited so as to not exceed guidelines for sodium and chloride. An LSI of 0.2 cannot be achieved without violating guidelines for sodium and chloride.	Delion, N., et al. (2004) *Desalination*, 165: 323–334.

(continued)

Table 2.1 (Continued)

Post-treatment process	Literature findings	Literature citation
Lime addition (continued)	3. $CaCl_2 + Na_2CO_3 + Cl_2$: desired alkalinity, calcium hardness and LSI values cannot be achieved using this method without violating guidelines for sodium and chloride. 4. $CaCl_2 + NaHCO_3 + Na_2CO_3 + Cl_2$: desired alkalinity, calcium hardness and LSI values cannot be achieved using this method without violating guidelines for sodium and chloride. • When comparing treatments, treatment 1 is superior as it provides the desired LSI, alkalinity and calcium hardness values without violating sodium and chloride guidelines. • When using this treatment technique, keep in mind that lime is available and cheap, but difficult to prepare and dose (need for preparation of lime water in saturator not to increase the turbidity of the treated water).	
Calcite bed filtration	• Passage of desalinated water dosed with carbon dioxide through a bed of limestone can produce water with a pH equal to that of the stabilization pH (pH_s). Theoretically, this process requires only 50% of the quantity of CO_2 required by the excess hydrated lime and CO_2; however, in practice the quantity is typically 65–85% of the required CO_2 quantity. Disadvantages of this process are that it is complex, labor intensive and requires high purity limestone to avoid deposition of impurities in permeate water	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	• Contacting limestone with CO_2 acidified desalinated water mineralizes the solution according to: $CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$. This process is simple and widely used. Limestone is cheaper than lime and half the CO_2 amount is consumed in the formation of the same minerals. The reaction is slow and does not reach completion, requiring neutralization of excess CO_2. It is difficult to properly design the dissolution bed as there is a lack of reliable data on the kinetics of dissolution of limestone by CO_2.	Hasson, D. and O. Bendrihem (2006) *Desalination*, 190 (1-3): 189–200
	• Limestone contactors can be used as an alternative to chemical addition to achieve stabilized finished water. The limestone contactor uses natural limestone and carbon dioxide to add calcium hardness and alkalinity to RO permeate. • Natural limestone contactors are more commonly found outside the United States where importing chemicals for post-treatment may be cost prohibitive, such as the Bahamas. One of the largest natural limestone contactor municipal scale installation is located on the island of Aruba, where natural coral is utilized as the source of limestone. • Critical issues to consider during limestone contactor design are: 1. Availability of NSF-approved limestone 2. Headloss characteristics of available limestone 3. Limestone storage and feed design characteristics 4. Controlled bypass capability for achieving target finished water hardness and alkalinity 5. Pre-limestone contactor pH adjustment for dissolution rate control (carbon dioxide should be used instead of sulfuric acid to avoid sulfate-based scale formation and alkalinity consumption)	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
	• It is necessary to make water slightly scale forming to create a protective deposit on internal surfaces of pipes and equipment. For that purpose, the LSI should be over zero and close to 0.2 ($SI > 1$, $SI \approx 1.2$) • Filtration on calcium carbonate using either calcite or dolomite combined with CO_2 injection can accomplish remineralization and a calcocarbonic balance (calcium carbonate equilibrated water). Na_2CO_3 can be injected to increase the LSI up to 0.2 ($SI = 1.2$).	Delion, N., et al. (2004) *Desalination*, 165: 323–334.

(continued)

Table 2.1 (Continued)

Post-treatment process	Literature findings	Literature citation
Calcite bed filtration (continued)	• The total alkalinity achieved with treatment is greater when compared with an equivalent treatment using lime and CO_2 injection. • When using this treatment technique, keep in mind that calcium carbonate is most of the time not available locally. Filters of large dimensions (filtration rate of 10 m/h) should be provided and they must be refilled regularly. But operation of the unit is very simple as the total alkalinity and calcium hardness to be reached only depend on CO_2 dosage.	
pH and/or alkalinity adjustment	• Low pH may increase corrosion rate; high pH may reduce corrosion rates • Lack of carbonate alkalinity makes permeate water very unstable and prone to wide variations in pH due to low buffering capacity. Lack of carbonate alkalinity and calcium may also contribute to increased corrosion, since protective calcium carbonate films cannot be deposited on pipe walls • Alkalinity provides stability in water and prevents variation in pH. It may contribute to the deposition of protective films. Highly alkaline water may cause corrosion in lead and copper pipes. • To develop post-treatment concepts for corrosion control following RO treatment, it is first necessary to have treatment goals. Alkalinity greater than or equal to 40 mg/L as $CaCO_3$ was chosen as a goal since it has been suggested by others that alkalinity less than this value is considered low and may result in poor buffering and pH variations	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.
	• To improve the taste of water, ions such as calcium and bicarbonates should be added. This will improve the taste of water as well as increase the alkalinity of the water. At the same time the water remineralization should not increase concentrations of chlorides and sodium, as their concentrations in the permeate water represent the majority of the TDS concentration. • Increasing the pH in the second pass of SWRO process enables ionization of boric acid and improves its rejection by membranes.	Delion, N., et al. (2004) *Desalination*, 165: 323–334.
Addition of corrosion inhibitors	• Corrosion inhibitors may be used to reduce the corrosivity of RO treated water. Phosphate and silicate inhibitors can form protective films on pipe walls that limit corrosion or reduce metal solubility. Orthophosphates react with pipe metal ions directly to produce a passivating layer. Silicate inhibitors can form a glasslike film on pipe walls.	AWWA (2007) *Reverse Osmosis and Nanofiltration Manual of Practice*
Primary and secondary disinfection	• Chlorine liquid or gas represents the cheapest whole life cost for the disinfection system. The choice of liquid or gas chlorine will depend on such issues as total chlorine requirement and chlorine withdrawal rate. • On-site generation of sodium hypochlorite would typically be 25% more expensive then liquid chlorine installation and up to 40% more expensive than chlorine gas installation. On-site generation using seawater is not really suitable for human consumption due to possible contamination of seawater with undesirable components. • Bulk delivery of sodium hypochlorite represents an option; however, it is the most costly disinfection option over the life of the plant. The high cost is due to deterioration of available chlorine with temperature.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	• It is important to consider the impact of disinfection processes on finished water. • Chlorine gas addition decreases pH and alkalinity due to formation of hypochlorous acid, while sodium hypochlorite and calcium hypochlorite addition will increase pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.1 (Continued)

Post-treatment process	Literature findings	Literature citation
Blending with fresh water supplies	• A cost effective option for post-treatment stabilization of the permeate is blending a percentage of freshwater containing sufficient levels of calcium hardness and alkalinity	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
	• If a blending water source is derived from a limestone or chalk geological formation, recarbonation and hence stabilization may be achieved to a greater extent than from non $CaCO_3$ bearing geological formations. • If blending from a $CaCO_3$ groundwater is possible, substantial savings may be made in the operating and capital cost of the post-treatment plant required. • The following water quality characteristics of the blend source should be taken into consideration when determining post-treatment process and blend ratios: – Groundwater alkalinity – Chloride and sulfate levels – Concentrations of “non desireable” contaminants – Available yield from the groundwater source	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	• Studies of TBW indicated that blending of alternative water supplies into the existing groundwater distribution system resulted in delivered water with inconsistent water quality. The effects of the blended waters on the distribution system water quality were unknown. • The study focused on distribution system effects of blending conventionally treated groundwater (G1), surface water process by enhanced treatment (S1) and desalted seawater by RO membranes (S2). The existing distribution system was equilibrated with G1. • G1 was high in alkalinity; S1 was high in sulfates; S2 was high in chlorides • The blending ratio of the different treated waters determined the quality of the finished water. • Iron release was experienced with alkalinity reduced below the background of G1 water • Copper release to drinking water increased with increasing alkalinity and decreasing pH • Lead release increased with increasing chloride and decreasing sulfate	Taylor, J. S., et al. 2005. *Water Science & Technology*. 51 (6-7): 285–291

Table 2.2
Brackish surface water post-treatment list by post-treatment process

Desalination technique	Post-treatment process	Description	Literature citation
RO NF EDR	pH and/ or alkalinity adjustment	• Low pH may increase corrosion rate; high pH may reduce corrosion rates • Lack of carbonate alkalinity makes permeate water very unstable and prone to wide variations in pH due to low buffering capacity. Lack of carbonate alkalinity and calcium may also contribute to increased corrosion, since protective calcium carbonate films cannot be deposited on pipe walls • Alkalinity provides stability in water and resists variation in pH. It may contribute to the deposition of protective films. Highly alkaline water may cause corrosion in lead and copper pipes. • To develop post-treatment concepts for corrosion control following RO treatment, it is first necessary to have treatment goals. Alkalinity greater than or equal to 40 mg/L as $CaCO_3$ was chosen as a goal since it has been suggested by others that alkalinity less than this value is considered low and may result in poor buffering and pH variations	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.
		• To improve the taste of water, ions such as calcium and bicarbonates should be added. This will improve the taste of water as well as increase the alkalinity of the water. At the same time the water remineralization should not increase concentrations of chlorides and sodium, as their concentrations in the permeate water represent the majority of the TDS concentration.	Delion, N., et al. (2004) *Desalination*, 165: 323–334.
	Addition of corrosion inhibitors	• Corrosion inhibitors may be used to reduce the corrosivity of RO treated water. Phosphate and silicate inhibitors can form protective films on pipe walls that limit corrosion or reduce metal solubility. Orthophosphates react with pipe metal ions directly to produce a passivating layer. Silicate inhibitors can form a glasslike film on pipe walls.	AWWA (2007) *Reverse Osmosis and Nanofiltration Manual of Practice*
	Primary and secondary disinfection	• Chlorine liquid or gas represents the cheapest whole life cost for the disinfection system. The choice of liquid or gas chlorine will depend on such issues such as total chlorine requirement and chlorine withdrawal rate. • On-site generation of sodium hypochlorite would typically be 25% more expensive then liquid chlorine installation and up to 40% more expensive than chlorine gas installation. On-site generation using seawater is not really suitable for human consumption due to possible contamination of seawater with undesirable components. • Bulk delivery of sodium hypochlorite represents an option; however, is the most costly disinfection option over the life of the plant. The high cost is due to deterioration of available chlorine with temperature.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• It is important to consider the impact of disinfection processes on finished water. • Chlorine gas addition decreases pH and alkalinity due to formation of hypochlorous acid, while sodium hypochlorite and calcium hypochlorite addition will increase pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.2 (Continued)

Desalination technique	Post-treatment process	Description	Literature citation
RO NF EDR (continued)	Blending with fresh water supplies	• A cost effective option for post-treatment stabilization of the permeate is blending a percentage of freshwater containing sufficient levels of calcium hardness and alkalinity	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
		• If a blending water source is derived from a limestone or chalk geological formation, recarbonation and hence stabilization may be achieved to a greater extent than from non $CaCO_3$ bearing geological formations. • If blending from a $CaCO_3$ groundwater is possible, substantial savings may be made in the operating and capital cost of the post-treatment plant required. • The following water quality characteristics of the blend source should be taken into consideration when determining post-treatment process and blend ratios: – Groundwater alkalinity – Chloride and sulfate levels – Concentrations of “non desireable” contaminants • Available yield from the groundwater source	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• Studies of TBW indicated that blending of alternative water supplies into the existing groundwater distribution system resulted in delivered water with inconsistent water quality. The effects of the blended waters on the distribution system water quality were unknown. • The study focused on distribution system effects of blending conventionally treated groundwater (G1), surface water process by enhanced treatment (S1) and desalted seawater by RO membranes (S2). The existing distribution system was equilibrated with G1. • G1 was high in alkalinity; S1 was high in sulfates; S2 was high in chlorides • The blending ratio of the different treated waters determined the quality of the finished water. • Iron release was experienced with alkalinity reduced below the background of G1 water • Copper release to drinking water increased with increasing alkalinity and decreasing pH • Lead release increased with increasing chloride and decreasing sulfate	Taylor, J. S., et al. 2005. *Water Science & Technology*. 51 (6-7): 285–291

Tables 2.3 and 2.4 include key literature on post-treatment of brackish and fresh groundwater, respectively. Within each table, literature findings are organized according to post-treatment process as applicable to the specified source water. In addition, tables include citations for the summarized literature findings.

Identification of Key Water Quality Parameters

It was also determined that many literature sources discussed post-treatment practices in relation to specific water quality parameters. Water quality parameters discussed included:

- pH
- Alkalinity
- Hardness
- Calcium concentration
- TDS concentration
- Sulfate to chloride ratio
- Turbidity
- Boron concentration

Identification of Key Corrosion Indices

With respect to water quality, it was clear that a number of post-treatment corrosion indices were used to describe water quality conditions as they related to post-treatment. However, of the articles reviewed, none consistently presented a common set of corrosion indices when describing post-treatment. For purposes of clarity, a list of corrosion control indices that were most commonly found in the literature are provided below along with a brief explanation of their significance:

- **Langelier saturation index (LSI):** reflects the difference between the measured pH and the stabilization pH, pHs. An LSI less than zero indicates an aggressive water and an LSI greater than zero indicates a scale forming water (Delion, et al., 2004).
- **Saturation Index (SI):** similar to the LSI; however, an SI less than one indicates an aggressive water and an LSI greater than one indicates a scale forming water (Delion, et al., 2004).
- **Calcium carbonate precipitation potential (CCPP):** a quantitative measure of the precise potential of a solution to precipitate or dissolve $CaCO_{3(s)}$. It is beneficial to use this index in conjunction with the LSI, as the LSI gives an indication of the state of $CaCO_{3(s)}$ saturation, and CCPP gives information about the potential amount of $CaCO_{3(s)}$ that would precipitate or dissolve (Lahav and Birnhack, 2007).
- **Larson's ratio:** calculated from the relative ratio of the total of chloride and sulfate ions to the total alkalinity of the water. Index values greater than 0.4 indicate more corrosive water; a value less than 0.2 indicate a non-corrosive water (Delion, et al., 2004).
- **Ryznar index:** quantitatively defines the aggressiveness or scaling potential of aerated water (Delion, et al., 2004).

Table 2.3
Summary of literature findings for brackish groundwater post-treatment processes

Desalination technique	Post-treatment process	Description	Literature citation
RO NF EDR	Decarbonation (degasification)	• CO_2 stripping, followed by lime or caustic soda addition, leads to corrosive and non-buffered water	Delion, N., et al. (2004) *Desalination*, 165: 323–334.
		• Decarbonation, or removal of excess carbonic acid, may be required due to the presence of high concentrations of carbonic acid that is typically accompanied by low pH. It will help increase the finished water pH. • Carbonic acid may result from the conversion of bicarbonate when acid is added to RO feed water as a method of controlling calcium carbonate scaling on the RO membrane. • Decarbonation is typically used in combination with other post-treatment processes, since it may be beneficial to convert some carbonic acid back to bicarbonate alkalinity. Combined use of decarbonation with pH adjustment may be more economical, since this will help control the cost of chemicals used to increase pH while still producing the desired pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.
	Hydrogen sulfide stripping	• Aeration and oxidation are the two primary means for removing hydrogen sulfide; incomplete chemical reactions in the process are often responsible for formation of polysulfide complexes and elemental sulfur, which manifest themselves as turbidity in the finished water	Lyn, T. L. and J. S. Taylor. 1992. *Journal AWWA*, 84: 103.
		• Membranes do not remove small, uncharged molecular contaminants or dissolved gases such as carbon dioxide, hydrogen sulfide and methane. • If hydrogen sulfide is present in a source groundwater, it must be removed, typically by packed tower or air stripping processes. • When sulfides are removed in the stripping process, the air stripping tower off-gas needs to be treated to remove gaseous sulfide to prevent odor and external corrosion issues on surrounding buildings and infrastructure • The stripping of carbon dioxide and hydrogen sulfide raises the pH and reduces the amount of base needed to perform stabilization.	Duranceau, S. J., et al. 1999. *Journal AWWA*. 91(5): 85–96
	pH and/or alkalinity adjustment	• Low pH may increase corrosion rate; high pH may reduce corrosion rates • pH adjustment can be used with permeates high in dissolved CO_2 concentration (carbonic acid) as an increase in pH will result in the conversion of some carbonic acid back to bicarbonate alkalinity. • Lack of carbonate alkalinity makes permeate water very unstable and prone to wide variations in pH due to low buffering capacity. Lack of carbonate alkalinity and calcium may also contribute to increased corrosion, since protective calcium carbonate films cannot be deposited on pipe walls • Alkalinity provides stability in water and prevents variation in pH. It may contribute to the deposition of protective films. Highly alkaline water may cause corrosion in lead and copper pipes. • To develop post-treatment concepts for corrosion control following RO treatment, it is first necessary to have treatment goals. Alkalinity greater than or equal to 40 mg/L as $CaCO_3$ as chosen as a goal since it has been suggested by others that alkalinity less than this value is considered low and may result in poor buffering and pH variations	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.3 (Continued)

Desalination technique	Post-treatment process	Description	Literature citation
RO NF EDR (continued)	pH and/or alkalinity adjustment (continued)	• pH adjustment represents an economical approach to increasing the alkalinity of the permeate. The pH of the water can be increased by addition of caustic soda or lime. Increasing the pH will convert some carbonic acid to bicarbonate, thus increasing alkalinity. • When high concentrations of carbonic acid are not available in permeate water to convert the desired amount to bicarbonate alkalinity with pH adjustment, it may be necessary to supplement alkalinity with chemical treatment. • Hydroxide addition will increase the finished water alkalinity and pH, but not carbonate and bicarbonate alkalinity. Alkalinity of this form provides buffering capacity that will help prevent pH variations in the distribution system. • Addition of carbonic acid in the form of CO_2 followed by addition of caustic soda or lime will increase bicarbonate and carbonate alkalinity • A more costly method of adding carbonate-based alkalinity is the addition of sodium carbonate or sodium bicarbonate. It may be necessary to monitot dosage rates to make certain that finished water sodium levels do not exceed recommended guidelines (WHO specifies 200 mg/L)	
		• Typically, free CO_2 is readily available in BWRO permeate if acid dosing is applied in the pretreatment phase to control calcium carbonate scaling. The lower the pH of the feed water, the higher the concentration of CO_2 in the permeate. Caustic addition to permeate high in CO_2 concentration can shift the equilibrium converting CO_2 to bicarbonate, which will increase the alkalinity and stability of the finished water.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	Addition of corrosion inhibitors	• Corrosion inhibitors may be used to reduce the corrosivity of RO treated water. Phosphate and silicate inhibitors can form protective films on pipe walls that limit corrosion or reduce metal solubility. Orthophosphates react with pipe metal ions directly to produce a passivating layer. Silicate inhibitors can form a glasslike film on pipe walls.	AWWA (2007) *Reverse Osmosis and Nanofiltration Manual of Practice*
	Primary and secondary disinfection	• Chlorine liquid or gas represents the cheapest whole life cost for the disinfection system. The choice of liquid or gas chlorine will depend on such issues such as total chlorine requirement and chlorine withdrawal rate. • On-site generation of sodium hypochlorite would typically be 25% more expensive then liquid chlorine installation and up to 40% more expensive than chlorine gas installation. • Bulk delivery of sodium hypochlorite represents an option; however, it is the most costly disinfection option over the life of the plant. The high cost is due to deterioration over time of available chlorine with temperature.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• It is important to consider the impact of disinfection processes on finished water. • Chlorine gas addition decreases pH and alkalinity due to formation of hypochlorous acid, while sodium hypochlorite and calcium hypochlorite addition will increase pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.3 (Continued)

Desalination technique	Post-treatment process	Description	Literature citation
RO NF EDR (continued)	Blending with fresh water supplies	• A cost effective option for post-treatment stabilization of the permeate is blending a percentage of freshwater containing sufficient levels of calcium hardness and alkalinity	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
		• If a blending water source is derived from a limestone or chalk geological formation, recarbonation and hence stabilization may be achieved to a greater extent than from non $CaCO_3$ bearing geological formations. • If blending from a $CaCO_3$ groundwater is possible, substantial savings may be made in the operating and capital cost of the post-treatment plant required. • The following water quality characteristics of the blend source should be taken into consideration when determining post-treatment process and blend ratios: – Groundwater alkalinity – Chloride and sulfate levels – Concentrations of "non desireable" contaminants • Available yield from the groundwater source	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• Studies of TBW indicated that blending of alternative water supplies into the existing groundwater distribution system resulted in delivered water with inconsistent water quality. The effects of the blended waters on the distribution system water quality were unknown. • The study focused on distribution system effects of blending conventionally treated groundwater (G1), surface water process by enhanced treatment (S1) and desalted seawater by RO membranes (S2). The existing distribution system was equilibrated with G1. • G1 was high in alkalinity; S1 was high in sulfates; S2 was high in chlorides • The blending ratio of the different treated waters determined the quality of the finished water. • Iron release was experienced with alkalinity reduced below the background of G1 water • Copper release to drinking water increased with increasing alkalinity and decreasing pH • Lead release increased with increasing chloride and decreasing sulfate	Taylor, J. S., et al. 2005. *Water Science & Technology*. 51 (6-7): 285–291
	Bypass blending with raw water supply	• Blending remineralized desalinated water with treated brackish water is frequently the cheapest option for increasing total dissolved mineral content. • Only partial stabilization can be achieved by blending desalinated water with mineral rich brackish groundwater. Further treatments are necessary to achieve stabilization and water quality requirements.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.

Table 2.4
Summary of post-treatment literature findings for fresh groundwater

Desalination technique	Post-treatment process	Description	Literature citation
NF EDR	Decarbonation (degasification)	• CO_2 stripping, followed by lime or caustic soda addition, leads to corrosive and non-buffered water	Delion, N., et al. (2004) *Desalination*, 165: 323–334.
		• Decarbonation, or removal of excess carbonic acid, may be required due to the presence of a high concentration of carbonic acid in permate that is typically accompanied by low pH. Decarbonation will help increase the finished water pH. • Carbonic acid concentration may increase as a result of the conversion of bicarbonate when acid is added to RO feed water as a method of controlling calcium carbonate scaling on the RO membrane. • Decarbonation is typically used in combination with other post-treatment processes, since it may be beneficial to convert some carbonic acid back to bicarbonate alkalinity. Combined use of decarbonation with pH adjustment may be more economical, since this will help control the cost of chemicals used to increase pH while still producing the desired pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.
	Hydrogen sulfide stripping	• Aeration and oxidation are the two primary means for removing hydrogen sulfide; incomplete chemical reactions in the process are often responsible for formation of polysulfide complexes and elemental sulfur, which manifest themselves as turbidity in the finished water	Lyn, T. L. and J. S. Taylor. 1992. *Journal AWWA*, 84: 103.
		• Membranes do not remove small, uncharged molecular contaminants or dissolved gases such as carbon dioxide, hydrogen sulfide and methane. • If hydrogen sulfide is present in a source groundwater, it must be removed, typically by packed tower or air stripping processes. • When sulfides are removed in the stripping process, the air stripping tower off-gas needs to be treated to remove gaseous sulfide to prevent odor and external corrosion issues on surrounding buildings and infrastructure • The stripping of carbon dioxide and hydrogen sulfide raises the pH and reduces the amount of base needed to perform stabilization.	Duranceau, S. J., et al. 1999. *Journal AWWA*. 91(5): 85–96
	pH and/ or alkalinity adjustment	• Low pH may increase corrosion rates; high pH may reduce corrosion rates • pH adjustment can be used with permeates high in dissolved CO_2 concentration (carbonic acid) as an increase in pH will result in the conversion of some carbonic acid back to bicarbonate alkalinity. • Lack of carbonate alkalinity makes permeate water very unstable and prone to wide variations in pH due to low buffering capacity. Lack of carbonate alkalinity and calcium may also contribute to increased corrosion, since protective calcium carbonate films cannot be deposited on pipe walls. • Alkalinity provides stability in water and prevents variation in pH. It may contribute to the deposition of protective films. Highly alkaline water may cause corrosion in lead and copper pipes.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.4 (Continued)

Desalination technique	Post-treatment process	Description	Literature citation
NF EDR (continued)	pH and/ or alkalinity adjustment (continued)	• To develop post-treatment concepts for corrosion control following RO treatment, it is first necessary to have treatment goals. Alkalinity greater than or equal to 40 mg/L as $CaCO_3$ was chosen as a goal since it has been suggested by others that alkalinity less than this value is considered low and may result in poor buffering and pH variations • pH adjustment represents an economical approach to increasing the alkalinity of the permeate. The pH of the water can be increased by addition of caustic soda or lime. Increasing the pH will convert some carbonic acid to bicarbonate, thus increasing alkalinity. • When high concentrations of carbonic acid are not available in permeate water to be convert to the desired amount to bicarbonate alkalinity with pH adjustment, it may be necessary to supplement alkalinity with chemical treatment. • Hydroxide addition will increase the finished water alkalinity and pH, but not carbonate and bicarbonate alkalinity. Alkalinity of this form provides buffering capacity that will help prevent pH variations in the distribution system. • Addition of carbonic acid in the form of CO_2 followed by addition of caustic soda or lime will increase bicarbonate and carbonate alkalinity • A more costly method of adding carbonate-based alkalinity is the addition of sodium carbonate or sodium bicarbonate. It may be necessary to monitor dosage rates to make certain that finished water sodium levels do not exceed recommended guidelines (WHO specifies 200 mg/L)	
		• Typically, free CO_2 is readily available in permeate if acid dosing is applied in the pretreatment phase to control calcium carbonate scaling. The lower the pH of the feed water, the higher the concentration of CO_2 in the permeate. Caustic addition to permeate high in CO_2 concentration can shift the equilibrium converting CO_2 to bicarbonate, which will increase the alkalinity and stability of the finished water.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
	Addition of corrosion inhibitors	• Corrosion inhibitors may be used to reduce the corrosivity of RO treated water. Phosphate and silicate inhibitors can form protective films on pipe walls that limit corrosion or reduce metal solubility. Orthophosphates react with pipe metal ions directly to produce a passivating layer. Silicate inhibitors can form a glasslike film on pipe walls.	AWWA (2007) *Reverse Osmosis and Nanofiltration Manual of Practice*
	Primary and secondary disinfection	• Chlorine liquid or gas represents the cheapest whole life cost for the disinfection system. The choice of liquid or gas chlorine will depend on such issues as total chlorine requirement and chlorine withdrawal rate. • On-site generation of sodium hypochlorite would typically be 25% more expensive then liquid chlorine installation and up to 40% more expensive than chlorine gas installation. • Bulk delivery of sodium hypochlorite represents an option; however, is the most costly disinfection option over the life of the plant. The high cost is due to deterioration of available chlorine with temperature.	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• It is important to consider the impact of disinfection processes on finished water. • Chlorine gas addition decreases pH and alkalinity due to formation of hypochlorous acid, while sodium hypochlorite and calcium hypochlorite addition will increase pH and alkalinity.	Seacord, T. F., et al. 2003. AWWA Membrane Technology Conference. Atlanta, GA.

(continued)

Table 2.4 (Continued)

Desalination technique	Post-treatment process	Description	Literature citation
NF EDR (continued)	Blending with fresh water supplies	• A cost effective option for post-treatment stabilization of the permeate is blending a percentage of freshwater containing sufficient levels of calcium hardness and alkalinity	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37
		• If a blending water source is derived from a limestone or chalk geological formation, recarbonation and hence stabilization may be achieved to a greater extent than from non $CaCO_3$ bearing geological formations. • If blending from a $CaCO_3$ groundwater is possible, substantial savings may be made in the operating and capital cost of the post-treatment plant required. • The following water quality characteristics of the blend source should be taken into consideration when determining post-treatment process and blend ratios: – Groundwater alkalinity – Chloride and sulfate levels – Concentrations of “non desireable” contaminants • Available yield from the groundwater source	A. Withers (2005) *Desalination*, 179 (1-3):11–24.
		• Studies of TBW indicated that blending of alternative water supplies into the existing groundwater distribution system resulted in delivered water with inconsistent water quality. The effects of the blended waters on the distribution system water quality were unknown. • The study focused on distribution system effects of blending conventionally treated groundwater (G1), surface water process by enhanced treatment (S1) and desalted seawater by RO membranes (S2). The existing distribution system was equilibrated with G1. • G1 was high in alkalinity; S1 was high in sulfates; S2 was high in chlorides • The blending ratio of the different treated waters determined the quality of the finished water. • Iron release was experienced with alkalinity reduced below the background of G1 water • Copper release to drinking water increased with increasing alkalinity and decreasing pH • Lead release increased with increasing chloride and decreasing sulfate	Taylor, J. S., et al. 2005. *Water Science & Technology*. 51 (6-7): 285–291
	Bypass blending with raw water supply	• A cost effective option for post-treatment stabilization of the permeate is blending a percentage of freshwater containing sufficient levels of calcium hardness and alkalinity	Walker, S., et al. 2007. *Florida Water Resources Journal*. 35–37

CHAPTER 3
PERMEATE POST-TREATMENT PRACTICES QUESTIONNAIRE

UTILITY QUESTIONNAIRE

A utility questionnaire was developed and distributed to the in-kind participating utilities in this research project. Other utilities were also sent the utility questionnaire; however, they did not directly participate in the workshops (see Chapters 4 and 5). A survey mailing list was developed based on information obtained through internet searches of industry, academic and regulatory sources. The utility questionnaire was organized using information obtained from the literature review and from individual participant utility phone interviews conducted by UCF.

The questionnaire included questions relative to post-treatment stabilization options and impacts to the distribution system and water quality data. The questionnaire required documentation of the post-treatment operations used and their sequence, water quality characteristics, operation information, general capital, and maintenance cost for post-treatment. A total of eighty-three questionnaires were distributed, of which twenty-five (30 percent response level) were returned and their responses used for data analysis. The specific names of participating utilities have been withheld in order to respect the privacy of these utilities. Instead of referring to utilities by name they have been assigned a reference number. In discussing information reported by participating utilities, the utilities will be referred to by their assigned number.

A copy of the utility questionnaire that was distributed to participating utilities is located in Appendix B. The questionnaire was organized and categorized into seven sections:

1. Section I requested general information about the desalting facility (or facilities).
2. Section II requested more specific plant characteristics along with a plant schematic showing pre-treatment and post-treatment processes.
3. Section III was intended to obtain post-treatment information for each facility with specific information on water quality.
4. Section IV sought information with regard to permeate quality, blend, and point-of-entry (POE) quality.
5. Section V requested information on post-treatment operation.
6. Section VI was designed to obtain information on post-treatment operation and maintenance costs.
7. Section VII was seeking information on lessons learned and/or major issues experienced with respect to post-treatment operations and practices.

SURVEY RESPONSE

Section I: Background Information

This section included identification and classification information including the plant name, address, total dissolved solids (TDS) levels, source water (i.e., groundwater under the direct influence of surface water). Respondents indicated the type of source water their desalination plant processed, with seven categories identified below:

Table 3.1
Plant characteristics

Number	Water source	Facility type
1	Ocean well	RO
2	Brackish water well	RO
3	Brackish water well	RO
4	Fresh groundwater well	RO
5	Lake/reservoir	RO
6	Brackish water well	RO
7	Fresh groundwater well	RO
8	Brackish water well	RO
9	Brackish water well/mountain spring	RO
10	Gulf/bay	RO
11	Secondary treated water	RO
12	Fresh groundwater well	RO
13	Brackish water well	RO
14	Brackish water well	RO
15	Brackish water well	RO
16	Brackish water well	RO
17	Fresh groundwater well	RO
18	Fresh groundwater well	RO
19	Brackish water well	RO
20	Brackish water well	RO
21	Fresh groundwater well	NF
22	Brackish water well	RO
23	Secondary treated water	RO
24	Lake/reservoir	EDR
25	Ocean well	RO

1. Seawater [SW]: (20,000–35,000 mg/L TDS)
2. High Brackish Groundwater [GW]: (>7,500–<20,000 mg/L TDS)
3. High Brackish Surface Water [SFW]: (>7,500–<15,000 mg/L TDS)
4. Low Brackish GW: (1,000–5,000 mg/L TDS)
5. Low Brackish SFW: (1,000–2,500 mg/L TDS)
6. Fresh GW: (<1,000 mg/L)
7. Fresh SFW: (<1,000 mg/L)

Table 3.1 lists the participating utilities by reference number, water source and facility type. Each utility has been assigned a number, 1 to 25, to be used for identification purposes in order to maintain the integrity and reputation of utilities, especially those who reported information regarding operational problems and/or water quality issues.

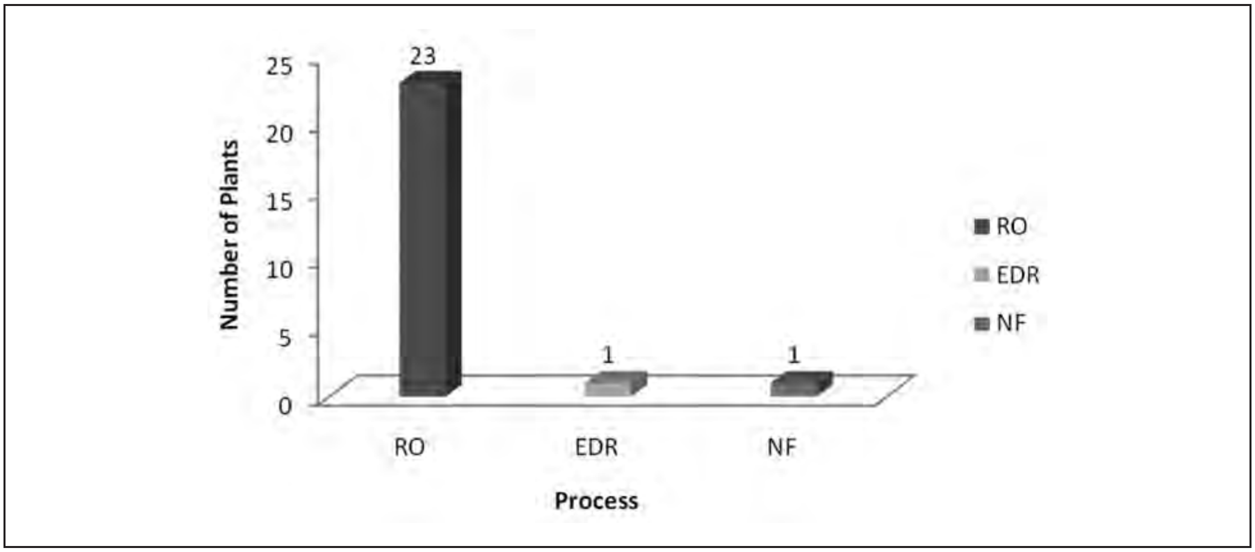


Figure 3.1 Distribution of plants surveyed

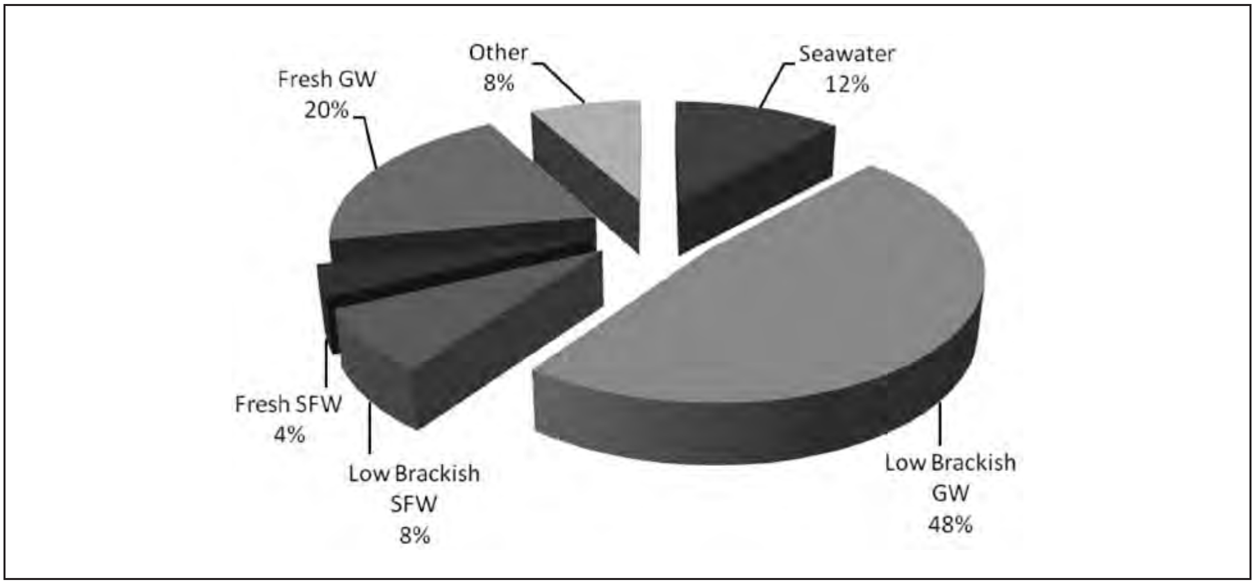


Figure 3.2 Plant type categorized by feedwater TDS

Figure 3.1 presents information on utility's membrane treatment process. Responses indicated that indicated ninety-two percent of the plants used RO membranes in their treatment process. The remainder of plants that responded were divided between EDR and NF treatment processes. Of those water purveyors reporting, forty-eight percent of the utilities indicated that low brackish GW was the feed water type supplying their desalting process, as shown in Figure 3.2. None of the responding organizations were classified as either highly brackish GW or highly brackish SFW. Twenty percent of the plants reporting indicated that they utilize fresh GW, and twelve percent treated SW. Eight percent of the reporting plants represented low brackish SFW, and four percent utilized fresh SFW. Eight percent of the respondents reported treating water not listed in the defined categories presented herein. The data supports the observations that synthetic

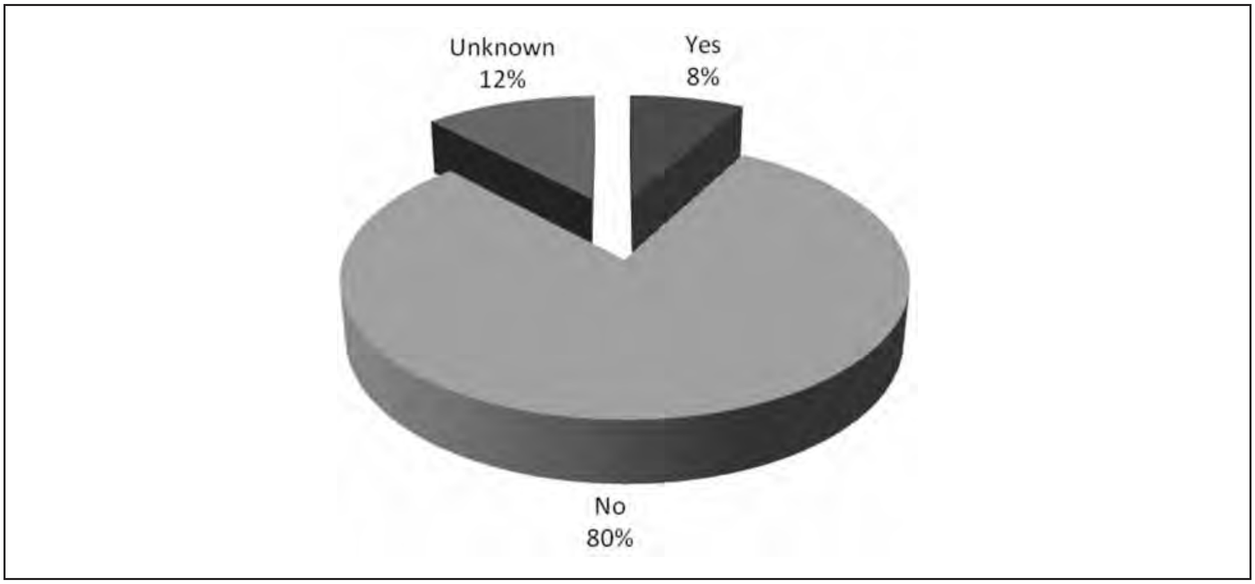


Figure 3.3 Is your groundwater under the influence of surface water?

membrane processes are not readily employed for treatment of high or low brackish surface water supplies; however, their use is increasing (Wangnick, K., 2004)

Figure 3.3 shows the percentage of utilities treating waters that are considered groundwater under the influence of surface water (GWUI). Twelve percent of the respondents were uncertain if their source water was considered GWUI. Eighty percent of the responding utilities indicated that their groundwater was not influenced by surface water. This may be significant for utilities employing desalination of GWUI supplies since treatment techniques will have to take into consideration several SDWA requirements such as the SWTR, DBP and GWR regulations where by-pass blending is implemented. Brackish groundwater sources would not require the degree of treatment for by-pass needs as would brackish surface water supplies, or that of seawater sources. As the application of synthetic membrane processes to brackish surface and brackish GWUI supplies increases then issues related to GWUI will impact the ability of a water purveyor to implement blending using by-pass of GWUI and most certainly would also alter post-treatment strategies.

Figure 3.4 presents the different types of ownership classification of the respondent utilities, with fourteen of the twenty-five desalting plants being publicly owned water treatment facilities, and an additional five of the utilities reported to be classified as a water authority. Of the remaining utilities, five were classified as other and one classified as private.

One component of the questionnaire was aimed at categorizing utilities according to their water quality goals. Those surveyed 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. This aspect of the questionnaire further defined the type of TDS that was being treated. As shown in Figure 3.5, of the twenty-five reporting utilities, seventeen plants listed salt removal as the major water quality driver. In addition, 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). A portion of the respondents reported that some other driver was responsible for the decision to use a desalting process, and none reported the use of the technology for synthetic organic compound (SOC) removal.

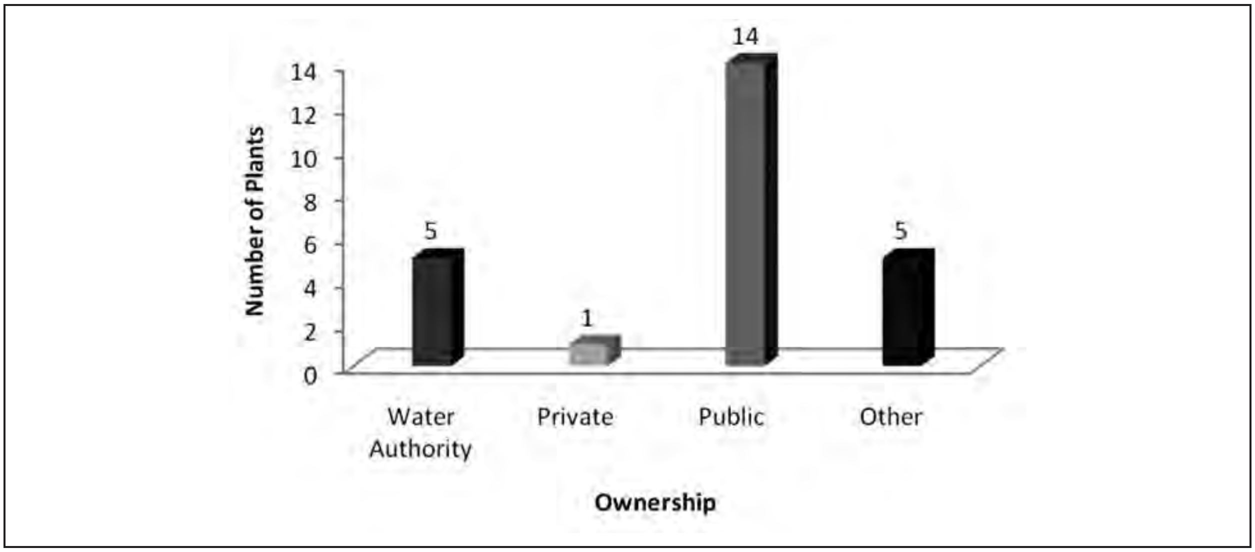


Figure 3.4 Type of ownership

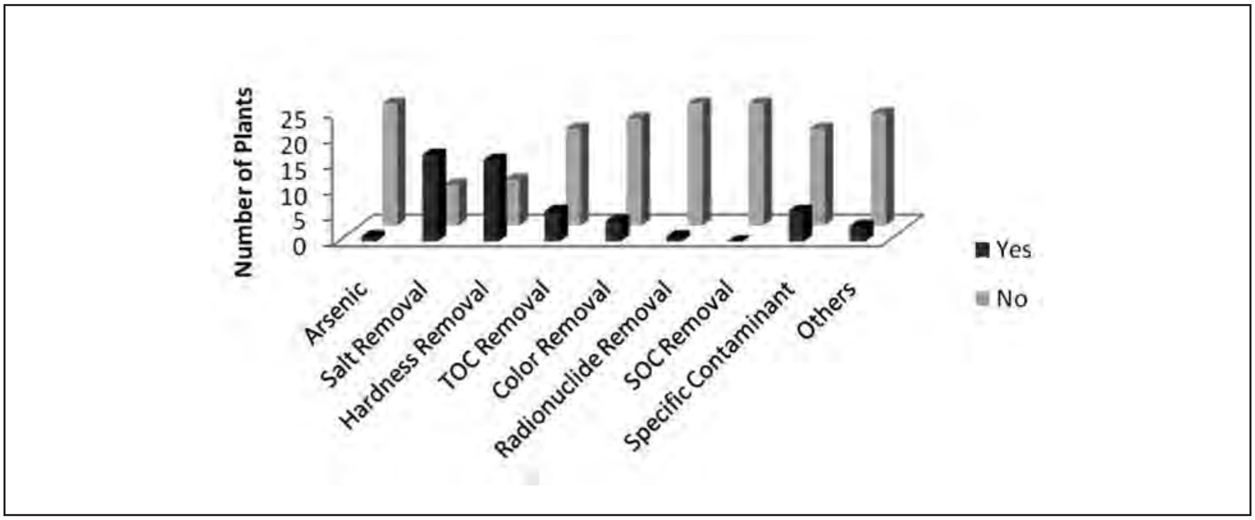


Figure 3.5 Water quality driver

Section II: Plant Characteristics

Concerning plant characteristics, evaluation of the responses revealed that seventy-two percent of the plants had a design hydraulic capacity between one and fifteen MGD. Detailed representations are shown in Figure 3.6, where twelve percent of the respondents had design hydraulic capacities of less than one MGD, yet sixteen percent were greater than 15 MGD.

Seventy-two percent of the utilities indicated that their facility had a design that called for an expansion, as indicated in Figure 3.7; and the remainder reported they did not have a design that included an expansion. Reported values for the feed water recovery is shown in Figure 3.8, and ranged from 25 to 95 percent recovery. From the graph, it can be seen that most RO facilities have an average feed water recovery between seventy to ninety percent, keeping in mind that a majority of these facilities reported low brackish groundwater as the source water. Those RO facilities using

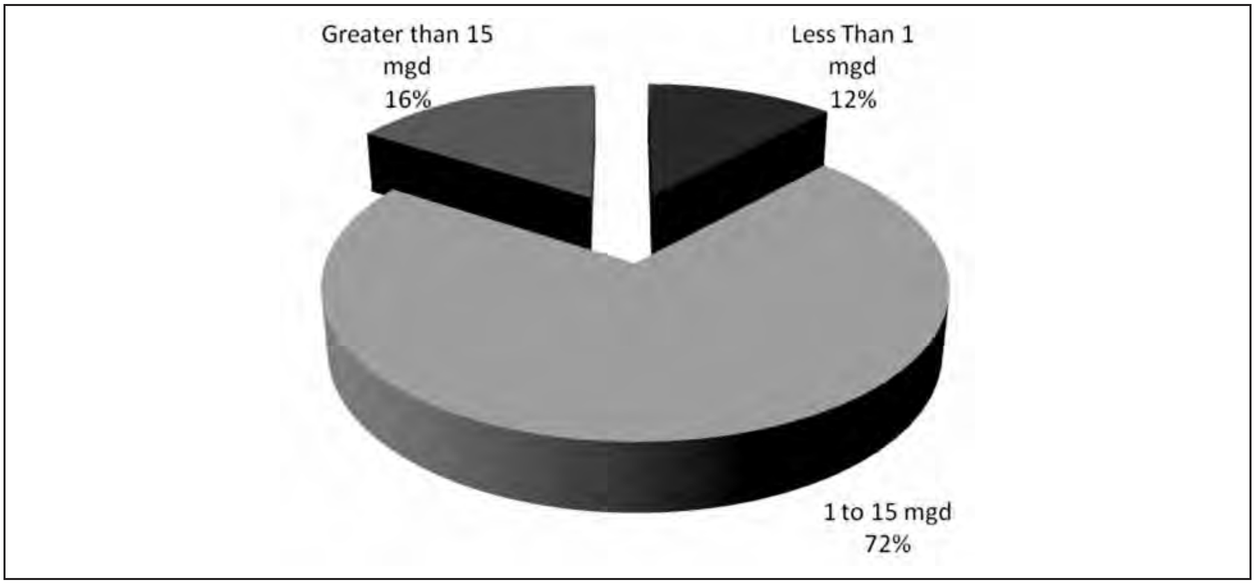


Figure 3.6 Hydraulic capacity

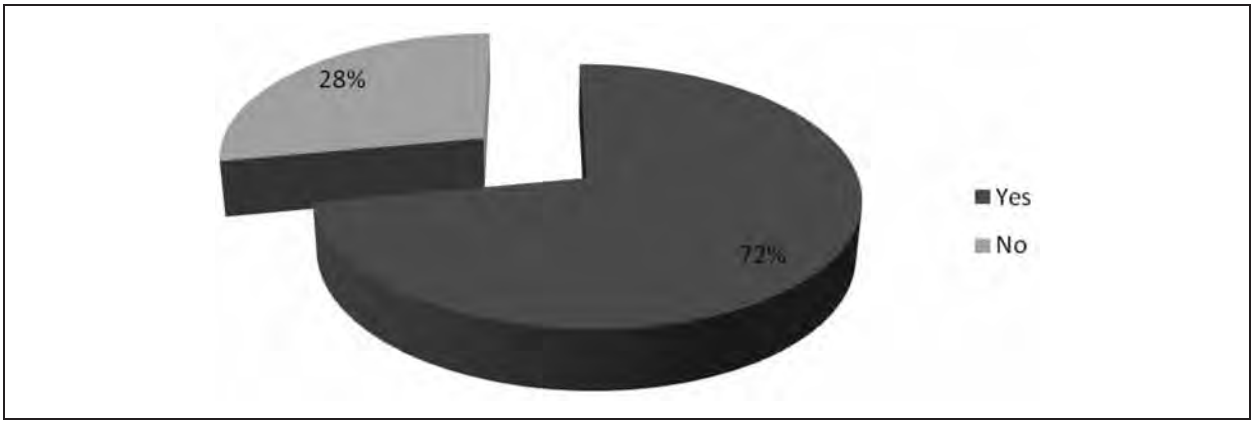


Figure 3.7 Plane originally designed for expansion

an ocean well as the source water, plant numbers 1 and 25, reported recoveries of approximately forty percent or less. Figure 3.8 shows the NF facility, plant number 21, reported a percent recovery of 90%, which is in the typical range of 85% to 90% recovery. The normal range for EDR process percent recovery is 75% to 90%; however, the value reported by the EDR plant, plant number 24, was approximately 25% as shown in Figure 3.8. Figure 3.9 presents the reported flux values that the treatment plants were designed around. The design pressure of each of the participating utilities is presented in Figure 3.10.

Each facility was asked to identify the end use of permeate, as shown in Figure 3.11. Most plants (seventy-seven percent) reported only one end use of the permeate water, that being potable water, with only a few plants reporting alternative end-uses. Seven percent of permeate use included irrigation and 6% was listed as an industrial end-use. Additionally, 7% of the respondents reported using permeate to recharge groundwater, and the remaining 3% used the permeate to create a seawater intrusion barrier. Distribution of source water for the facility of each survey respondent can

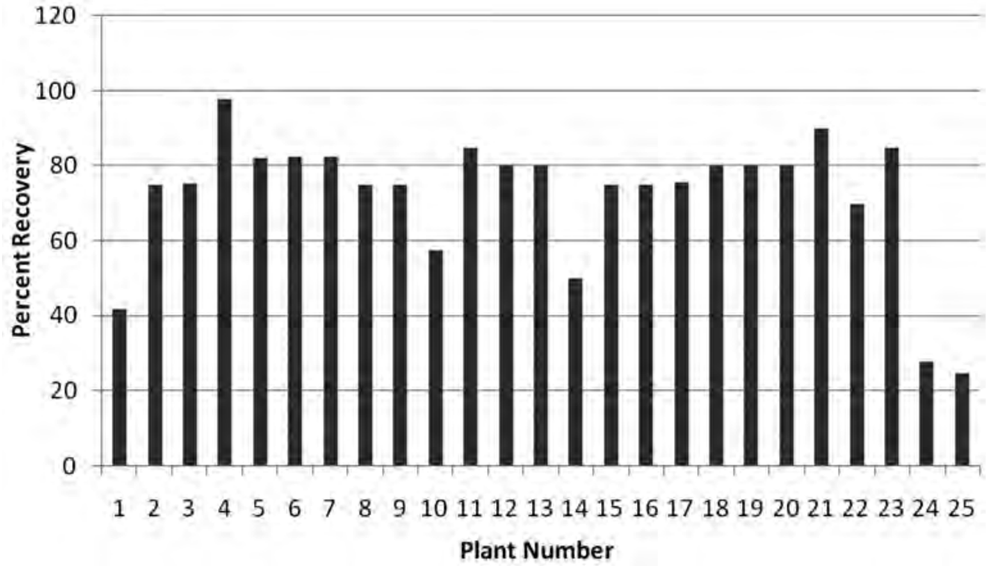


Figure 3.8 Design percent RO feedwater recovery

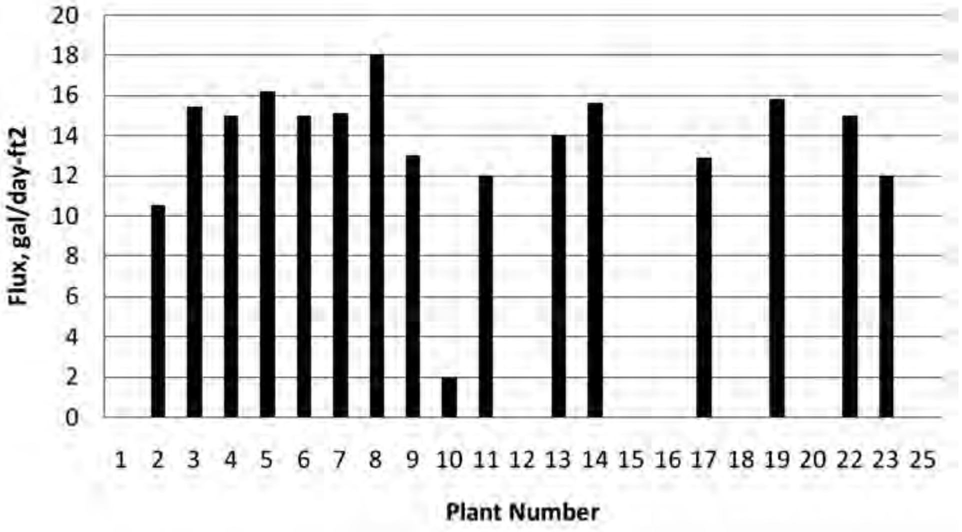


Figure 3.9 Design RO membrane flux

be seen in Figure 3.12. Approximately 15% of the plants reported using a brackish water well for their source water.

Section III: Post-Treatment Information

Table 3.2 summarizes findings related to post-treatment types and associated disinfection practices. Regarding post-treatment, 72% percent of the plants use caustic chemical addition and 64% percent rely on blending. Most plants used a combination of disinfection practices for

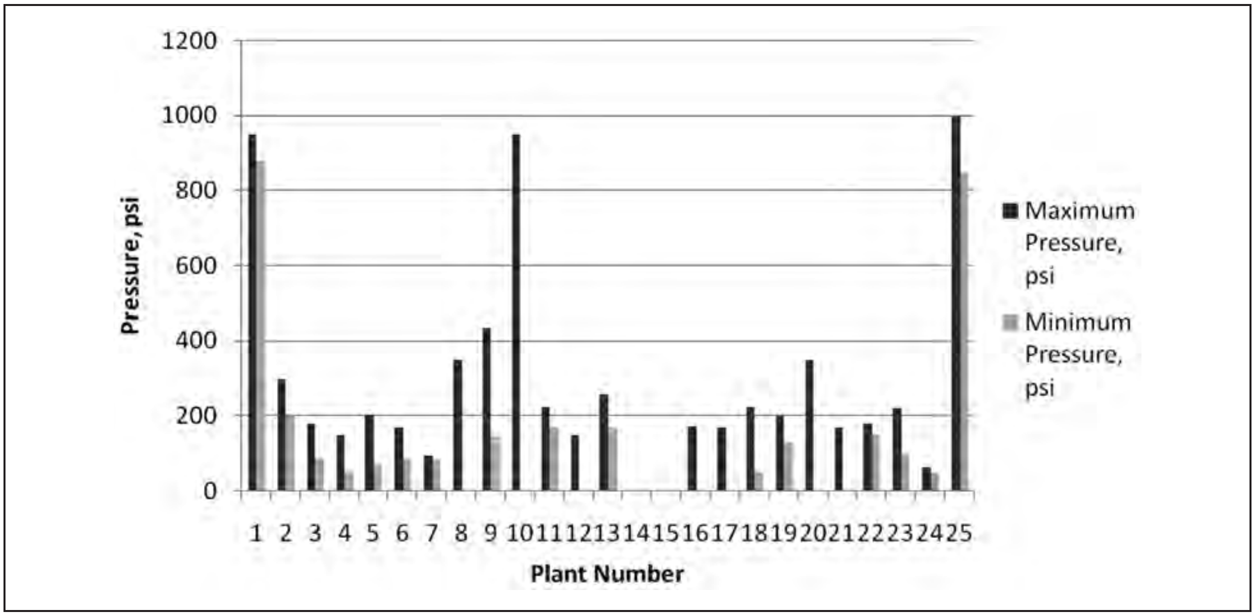


Figure 3.10 Design pressure

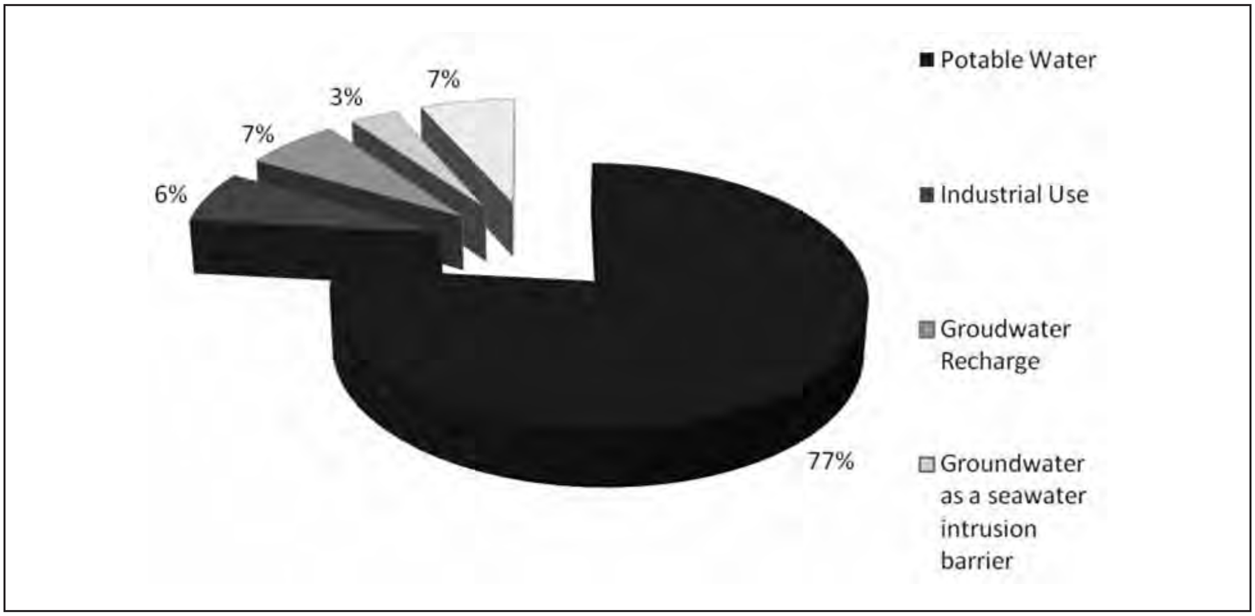


Figure 3.11 Permeate water end-use

post-treatment. For primary disinfection, 68% percent of the plants use chlorine addition and for secondary treatment 44% percent of the plants implemented chloramines. None of the respondents reported using ozone. Table 3.3 details the response given by the facilities in regards to post-treatment disinfection and residual goals at the facility. Reported disinfection chemicals include free chlorine and chloramines. Goals for free chlorine leaving the facilities ranged from 0.5 mg/L

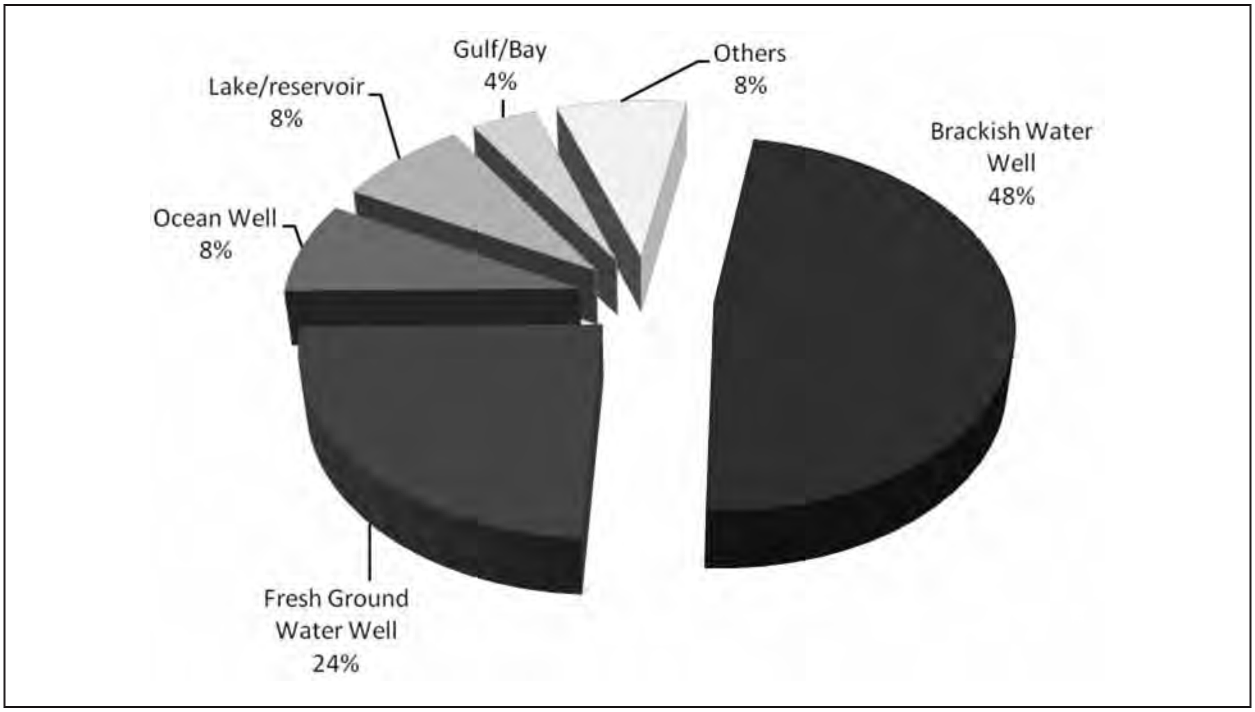


Figure 3.12 Source water

Table 3.2
Post-treatment types and disinfection

Question	Response (%) Yes	No
Post-treatment Type:		
Air Stripping	28	72
Degasification	64	36
Caustic Chemical Addition	72	28
Corrosion Inhibitor Addition	32	68
Blending	64	36
Treated SW	12	88
Treated GW	36	64
Other	36	64
Disinfection: Primary		
Chlorine	68	32
Ozone	0	100
UV	8	92
Chlorine Dioxide	4	96
Other	20	80
Disinfection: Secondary		
Chlorine	12	88
Chloramines	44	56
Other	4	96

Table 3.3
Post-treatment disinfection and disinfection residual goals

Plant number	Comments
1	0.25 ppm free chlorine residual
2	3.5 mg/L POE residuals 4 log virus removal
3	2–5 mg/L combined chlorine at POE 1.0 mg/L minimum in distribution system
4	0.5 mg/L free chlorine leaving DATS 1.0 mg/L free chlorine in transmission main 2.5 mg/L chloramines entering distribution system 1.0 mg/L chloramines minimum in distribution system
5	0.5 ppm chlorine dioxide
6	1.0 mg/L
7	4.0 mg/L chloramines leaving the facility 1.0 mg/L of chloramines residual at the extremities of the distribution system
8	1.0 mg/L
9	2.0 ppm in the finished water tank
10	4.0 mg/L free chlorine 4.0 mg/L Chloramines
11	3 log removal
12	1.5 ppm
13	2.5 to 3 ppm free chlorine
14	Finished water (permeate + blend) is dosed with 4 mg/L 12% Sodium Hypochlorite to maintain approximate 1.5 mg/L free Cl_2 residual
15	1.4 ppm chlorine residual 4-log removal
16	1.8 mg/L free chlorine
17	4 mg/L chloramines Free N<0.1
18	3 to 3.2 free residual at clearwell
19	2 to 3 mg/L total chlorine
20	3.0 ppm residual 4 log removal
21	3.0 ppm residual 4 log removal
22	3.2 to 3.7 mg/L of disinfectant (chlorine)
23	Zero detection of total and fecal coliform
24	1–2 mg/L of disinfectant (combined chlorine)
25	3.5 mg/L total disinfectant (combined chlorine)

Table 3.4
Have you experienced any post-treatment problems within the plant?

Question	Response (%) Yes	Response (%) No
Have you experienced any post-treatment problems within the plant?		
Blending limitations	8	92
Scaling of degasification/stripping towers	16	84
Biological growth in degasification/stripping towers	20	80
Chemical injector plugging	16	84
Issues with cleaning post-treatment equipment	0	100
White water formation	4	96
Corrosion events	12	88
Colored or red water	16	84
Others	20	80

to 4 mg/L. Log removal of contaminants ranged from 3 to 4 log removal, representing 99.9% to 99.99% reduction of contaminants. Residual goals ranged from 2–4 mg/L.

The reliability of a post-treatment system is important for achieving stabilized water that meets regulatory requirements. Common issues noted by those surveyed included biological growth in the degasification/stripping towers, scaling of the degasification/stripping towers and red water events. Table 3.4 provides a more detailed summary of the post-treatment issues reported by the respondents. Failure of an effective post-treatment process may have a significant impact on the water quality within the distribution system. Utility responses revealed that the choice of and sequence of their post-treatment operations varied, therefore establishment of an effective post-treatment process is source water and site specific. A list of potential water quality impacts is presented in Table 3.5. 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. The information in Tables 3.4 and 3.5 should be taken into consideration when designing post-treatment processes and analyzing potential water quality impacts.

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. Table 3.6 lists descriptions given by the facilities concerning their respective blending or by-pass processes. 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.

Table 3.7 describes the post-treatment operations of each facility. This table lists the choice and sequence of post-treatment operations practiced by participating utilities. The sequence of post-treatment varied for each facility, further emphasizing the need to evaluate factors specific to synthetic membrane process, source water and plant location in the design of a post-treatment process. Most facilities utilized blending, pH adjustment using CO_2 or NaOH. Degasifiers were used for gas removal, and for disinfection chorine or chloramines addition was utilized.

Table 3.5
Any distribution system impacts noted?

Question	Response (%) Yes	Response (%) No
Distribution system impacts?		
Corrosion events (infrastructure)	16	84
Lead and copper rule impacts	4	96
Disinfection by-products	4	96
Taste and odor	0	100
Detention time prior to point of entry	4	96
Detention time after point of entry	0	100
pH stability	16	84
Disinfection residual stability	20	80
White water	0	100
Color	12	88
Red water/black water	24	76
Biological re-growth	12	88
Others	12	88

Table 3.8 shows that facilities utilize pH adjustment as the most common method for addressing issues related to pH control and establishing buffering content in permeate water. Caustic addition in the form of NaOH was one common method listed for pH adjustment. This method is successful in increasing the system pH; however, NaOH addition alone does not address issues related to buffering content. Some utilities reported using caustic addition in the form of caustic soda or soda ash to control pH. This method may be advantageous to NaOH addition as it will increase the system pH and increase the bicarbonate alkalinity concentration, which increases the buffering capacity of the water. Some utilities listed addition of caustic along with carbon dioxide for control of pH and buffering content. The caustic addition will elevate the system pH. This method can also address issues related to buffering content as the caustic addition coupled with carbon dioxide addition can increase the alkalinity of the water. 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.

Table 3.9 summarizes utility's methods of corrosion control. Eighty percent of the plants listed pH adjustment as their method for corrosion control; and blending represents sixty percent. Alkalinity adjustment and corrosion inhibitor addition were also cited as corrosion control measurses. Most plants did incorporate two or more methods for corrosion control in their facility.

Section IV: 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

Table 3.6
Blending or by-pass descriptions

Plant number	Comments
1	No Response
2	Lime softened and ion exchange water is blended with RO permeate
3	RO permeate produced goes through de-carbonation and is then blended with raw groundwater
4	Blend NF permeate with raw (untreated but disinfected) groundwater in the transmission main
5	Blend RO permeate with two different groundwater sources, the first source is used to blend at a ratio of 7 Mm3/y RO permeate to 30.1 Mm3/y groundwater and the second groundwater source used to blend is established at a ratio of 9.2 Mm3/y to 13.68 Mm3/y but fixed on TH of 1.5 mmol/L
6	Permeate blended with brackish feed water
7	Marginal blending occurs in two clear wells and is not adequate.
8	Adjust hardness and alkalinity
9	Blending water is filtered by Granular Activated Carbon filter then blended with RO permeate (manually control)
10	Finished water from seawater desalination plant blends with finished water from the regional SWTP. The blended product if adjusted for finished pH and alkalinity then blends with groundwater
11	Seventy percent post RO water goes to Decarbonation Towers-30% by passes
12	Blend up to 5% to add back some fluoride
13	By-pass 10% raw water through a cartridge filter into the product water
14	Six Percent of raw water is by-passed through 5 micron cartridge filters and blended with product water stream prior to degasification and post-treatment
15	Filtered with sand separators and micron filters has been treated with anti-scalant
16	RO product water blended with ion exchange treated raw water raw water which has be degasified and chlorinated to breakpoint
17	Thirty-three percent of filtered effluent is blended with permeate for stabilization. Fifty percent sodium hydroxide is added to permeate for pH adjustment
18	No Response
19	Raw bypass water is blended with permeate following the degasifiers but before chlorine and caustic addition
20	Finished water product form (Lime softening, RO, NF) is blended together on one blend tank and then pumped to onsite storage tanks. Cl_2, Caustic, and Fluoride are added in blend tank
21	Finished product water from (Lime Softening, NF, RO) is blended is and the pumped to onsite storage tank
22	Blend water is filtered raw water after the pre-filters. Blend 10% of the total permeate gallons from the RO units
23	After RO there is a partial bypass of flow around decarbonation with majority sent to decarbonation towers
24	No Response
25	No Response

Table 3.7
Sequence of post-treatment operations

Plant number	Comment
1	Degasification, NaOH for pH-adjustment, calcium hypochlorite disinfection.
2	pH adjustment, degasification, chlorination, ammonization, blending
3	Decarbonation, blend with sequestering agent caustic, disinfection
4	Free Chlorine and degasification
5	CO_2 dosage followed by NaOH to form HCO_3, transport, blending, pH correction with NaOH or CO_2, ClO_2 dosage distribution
6	Blending, pH control, disinfection, corrosion control
7	Addition of corrosion inhibitors, degasification, caustic and some blending
8	Blend with sand filtered groundwater and condition with caustic chemical followed by NaOCl
9	Degassification, caustic addition and blending with raw water bypass treated with GAC then NaOCl.
10	CO_2 followed by saturated lime injection, then final disinfection with free chlorine (sodium hypochlorite)
11	Barrier Injection=peroxide, UV, Decarbonation, lime, storage. Industrial Use=Decarbonation, 2nd pas RO (for some water) to industry
12	Calcium Chloride, chloramines
13	Degasifiers, clearwell CO_2 addition, caustic and corrosion inhibitor, fluoride
14	Product stream blended w 6% raw water addition of CO_2, degasification, Cl_2 to NaOH for pH adjustment and zinc ortho-PO_4 for corrosion control
15	Blend, degasification, chlorine and soda addition
16	Degasification, NaOH addition, Chlorine addition
17	Blend filtered/permeate and add free chlorine for .5 to .8 ppm dose; blend water enters 5 mg GST; Post disinfection is chloramination
18	Chemical feed to clear well offsite storage tank with chlorine booster
19	Degasifiers, blend, chlorine(hypo caustic agent and blend ahead of blend point) chlorine contact tank (2–4 hrs), ammonia, high lift pumps, distribution
20	Permeate water from the RO plant is sent to a Degasifier and the H_2S gas goes thought a scrubber. The finished water then goes to the blend tank
21	Permeate from the membrane plant is sent to a degasifer and then to the blend tank where it is blended and caustic sodium hypochlorite, and fluoride is added
22	Degasification, sodium hydroxide injection, sodium hypochlorite injection, clear well water pumped to GST's
23	Take blend of fully and partially decarbonated RO product water and add lime solution. Lime solution by adding powered form hydrated lime (CaOH) to decarbonated RO water in a slurry unit tank and sending slurry to a saturator. Saturator supernatant drawn off for addition to plant effluent water
24	Raise pH with NaOH
25	Degasification, NaOH addition,NH_3, Cl for disinfection

Table 3.8
Control of pH and buffering content on post-treatment

Plant number	Comment
1	No Response
2	Addition of NaOH and blending of water of low color and moderate hardness
3	Decarbonation, blend with sequestering agent, caustic, disinfection
4	Water is well buffered, membranes don't remove inorganic material, not required
5	Online measurements of pH controlling CO_2 and NaOH dosage
6	Only addition of poly-orthophosphate
7	Degasification, pH adjustment, some blending and addition of corrosion inhibitor
8	NaOH adjusting pH to 7.2
9	In line pH meter and conductivity
10	Yes, pH/ alkalinity adjustment facility
11	Lime Addition and decarbonation towers.
12	No Response
13	Addition of CO_2 then caustic alkalinity at 30 ppm
14	Addition of CO_2 and 50% NaOH
15	Soda ash only
16	pH control with caustic and blending from separate fresh groundwater supply. The groundwater supply is located inland from the brackish WTP site where fresh groundwater is treated through an ion exchange system prior to blending with RO permeate and simple bypass of raw fresh groundwater.
17	50% caustic from pH adjustment; 33% blend ratio for stabilization
18	Caustic Soda
19	With raw blend and caustic
20	pH is raised by blending with water from the lime softening plant and caustic soda
21	pH is raised by blending the water with the lime softening plant and adding caustic soda
22	Clear well target range of 8.2 to 8.5 for the pH. Sodium hydroxide metering pump is adjusted accordingly by the operators to maintain that range for pH
23	Use hydrated lime (CaOH) made into a solution via slurry mix system. Also, pH is controlled by controlling amount of bypass around decarbonation process
24	Raise the pH with caustic soda addition
25	NaOH addition

water, and the point-of-entry (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.

Figure 3.13 presents a plot of average temperature, pH, and alkalinity. A review of the collected information shows that the average pH and temperature of the permeate, blended water and

Table 3.9
Describe your method of corrosion control

	Response (%)		
Question	Yes	No	No Response
Describe your method of corrosion control			
pH adjustment	80	16	4
Alkalinity adjustments	24	72	4
Hardness adjustments	20	76	4
Corrosion inhibitor	28	68	4
Blending	60	36	4
Others	4	92	4

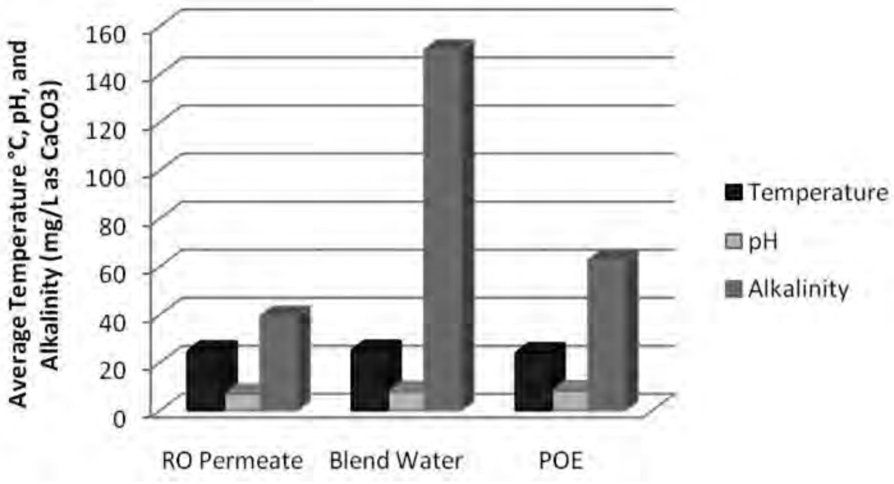


Figure 3.13 Average temperature, pH, and alkalinity for permeate, blend, and point of entry

finished water delivered to the point-of-entry (POE) to the distribution system do not change significantly across unit operations. However, the alkalinity of the blend water is appreciably different than the permeate and POE data 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 or is low in pH containing predominantly carbonic acid instead of carbonate alkalinity, which can be shifted to equivalent bicarbonate alkalinity with an increase in pH. 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, 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 a minimum of one milli-equivalent of alkalinity as $CaCO_3$ provides sufficient buffering for the distribution system.

Figure 3.14 summarizes the reported average turbidity and color data 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,

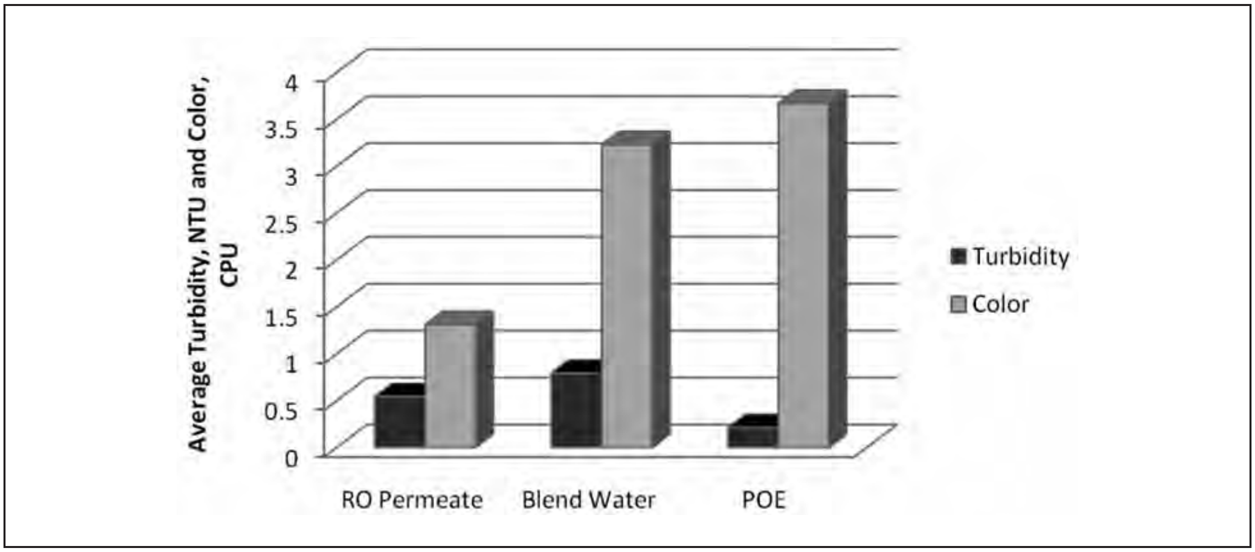


Figure 3.14 Average turbidity and color for permeate, blend, and point of entry

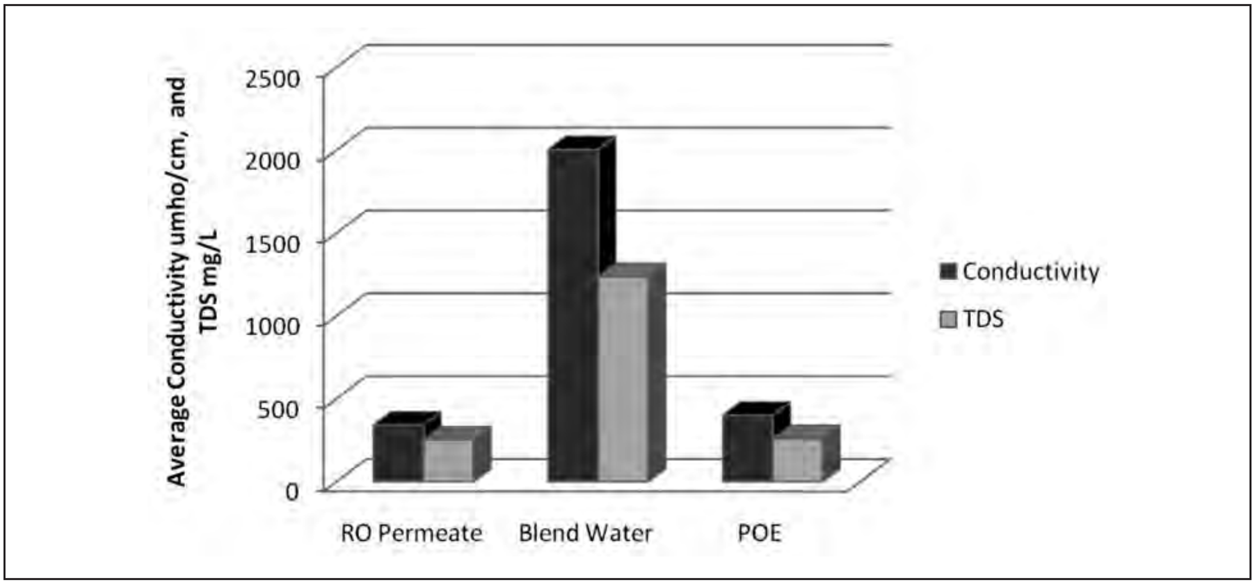


Figure 3.15 Average conductivity and TDS for permeate, blend, and point of entry

particularly if other water plants feed the same POE. In addition, the difference in turbidity between 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. Although color does vary by location, the difference between the POE (3.5 CPU) and permeate (1.1 CPU) are not significant.

Figure 3.15 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 pesented 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 blend water supply, which is not unreasonable since many plants by-pass the native

Table 3.10
Water quality parameters not consistently provided by respondees to the questionnaire

Water quality parameters
Hydrogen sulfide
Silica
Bromide
Algae
Heterotrophic plate count bacteria
Pseudomonas
Langelier saturation index
Ryznar index

raw water supply to blend with permeate to add stability economically. 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.

Table 3.10 provides a list of water quality parameters that were not consistently provided in the returned questionnaire responses (most utilities did not respond to this part of the questionnaire). These parameters (or indices) are not typically collected by water plant personnel, and the questionnaire confirmed that many of these parameters are only collected for use in special studies or other non-traditional plant operation protocols. This is not unexpected, but does allow for future consideration with regards to enhanced operations monitoring and improved post-treatment water quality data collection activities. However, enhancements to existing operating methods that would require the addition of several if not all of the parameters listed in Table 3.10 would result in an increase in the overall operating costs of the facilities.

Figure 3.16 presents permeate water quality data; specifically, sodium, calcium, magnesium, sulfate and chloride concentrations. Figure 3.16 illustrates that the permeate quality was predominantly comprised of sodium and chloride for the plants surveyed, and depleted in calcium and magnesium. This would be expected since the majority of the facilities that responded to the questionnaire utilized RO (Figure 3.1) and treated predominantly some form of brackish or seawater supply (Figure 3.2). In RO, the divalent constituents (calcium, magnesium, and sulfate) would be almost completely rejected by the membrane, resulting in permeate with sodium and chloride concentrations present in quantities controlled by diffusion through the membrane. Permeate water that was depleted in minerals was further conditioned by blending, as presented in Figure 3.17. Chloride appeared to be the controlling ion in terms of concentration present and upon which the total dissolved solids content would be based.

Figure 3.18 presents information with respect to several water quality parameters identified at the POE. Sodium, sulfate, and chloride are found to be present in higher concentrations at the POE than other constituents such as potassium, barium, calcium, iron, manganese, phosphate, aluminum, fluoride, and selenium. There is a portion of the respondents reporting magnesium, due to the blending impacts of by-pass water. A small amount of aluminum is present, most likely related to corrosion by-products of valves, pumps, and appurtenances and not necessarily as a result of the by-pass or blend water supplies.

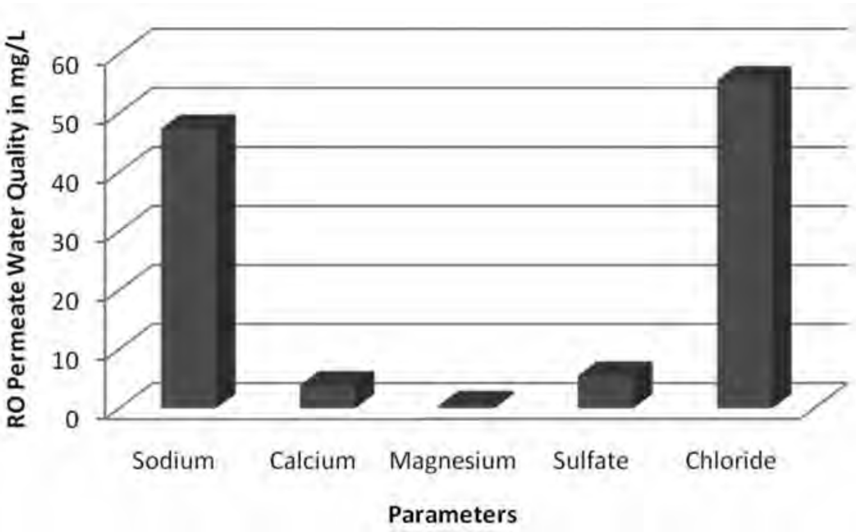


Figure 3.16 RO permeate water quality

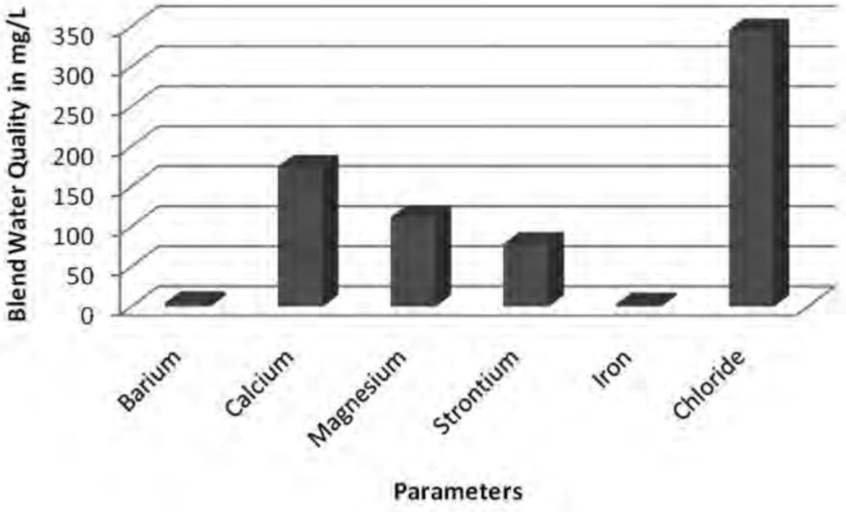


Figure 3.17 Blend water quality

Section V: Post-Treatment Operations

Several of the responding utilities provided data pertaining to post-treatment operations. Information requested included the average and maximum daily permeate production, and data regarding daily permeate and blend water flow rates. In addition, information regarding post-treatment chemicals and average dosage rates was requested. Blending ratio (as a percentage) and its control also was one component of the post-treatment operations survey. Figure 3.19 shows the frequency distributions of the daily permeate production at facilities reporting flow rates. Permeate production rates ranged from 0.12 MGD to 70 MGD across the respondents. Blend water flow rates are schematically represented as the frequency chart shown in Figure 3.20. Many of the

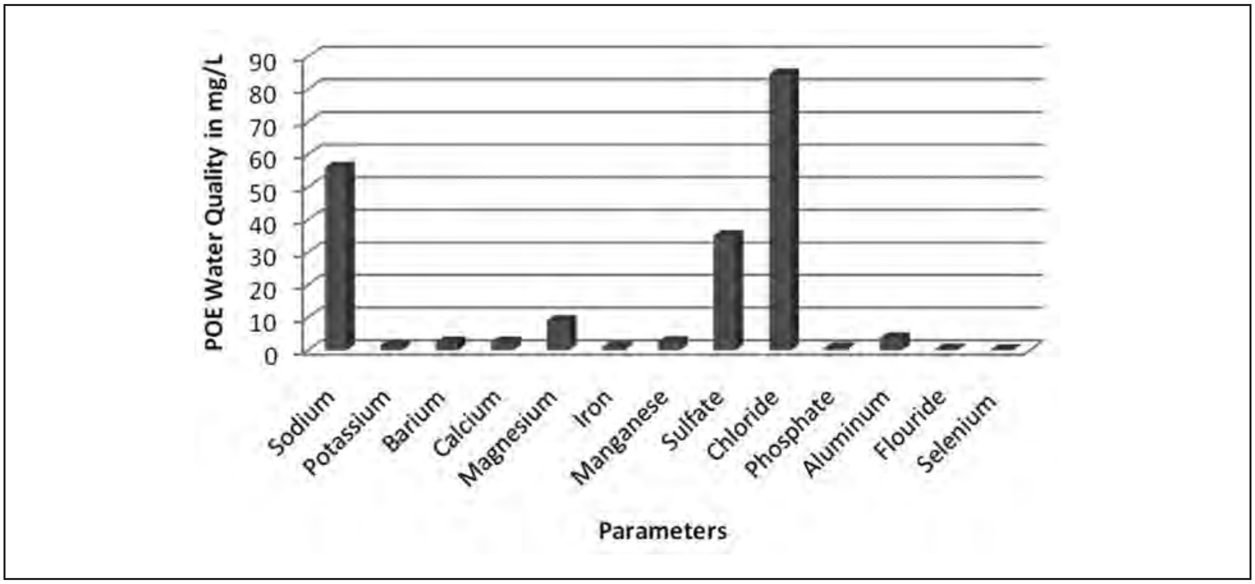


Figure 3.18 Point of entry water quality

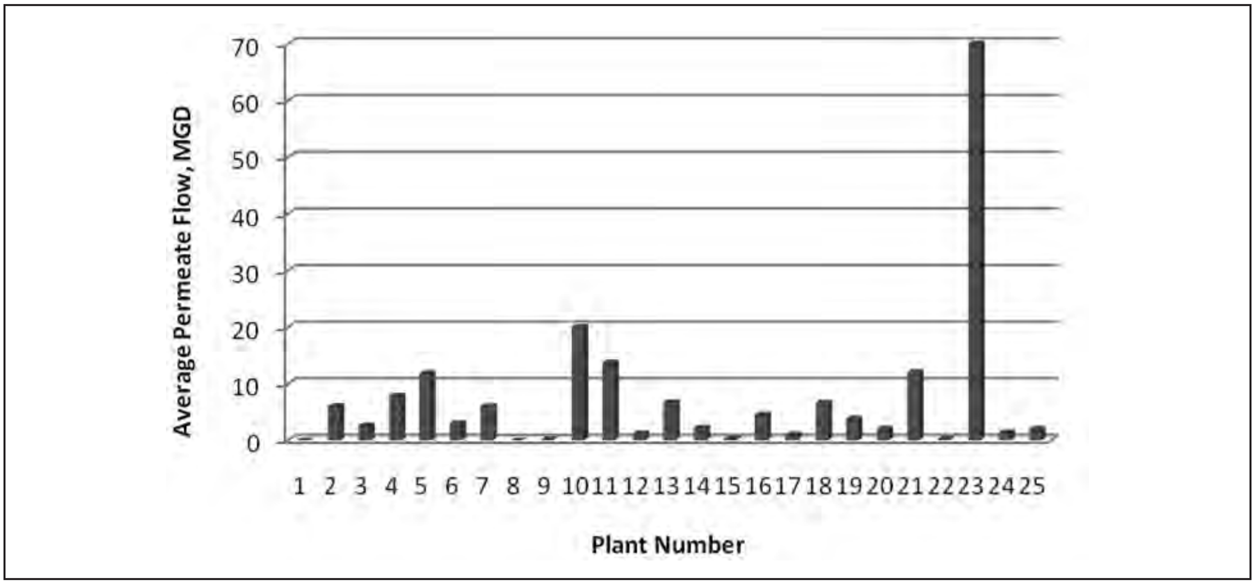


Figure 3.19 Frequency distribution of the average daily NF/RO permeate production

facilities reporting indicated that a significant amount of flow is blended across the facilities. Of the plants that were surveyed, the highest average flow of the blend water flow was approximately ten million gallons per day.

Section VI: 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. Figure 3.21 shows a representation of plant capacity versus operation and maintenance cost. There is not a strong correlation with plant capacity and costs given by the

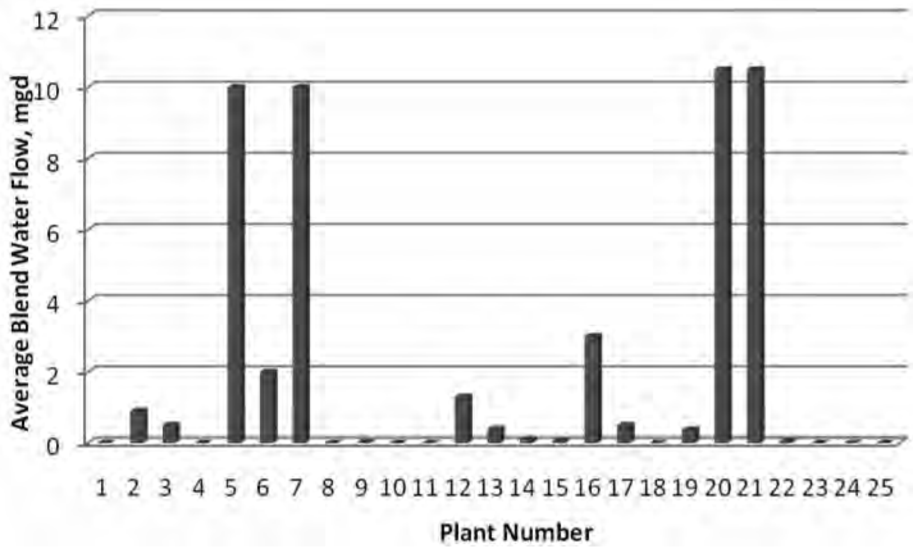


Figure 3.20 Frequency distribution of reported average blend flow

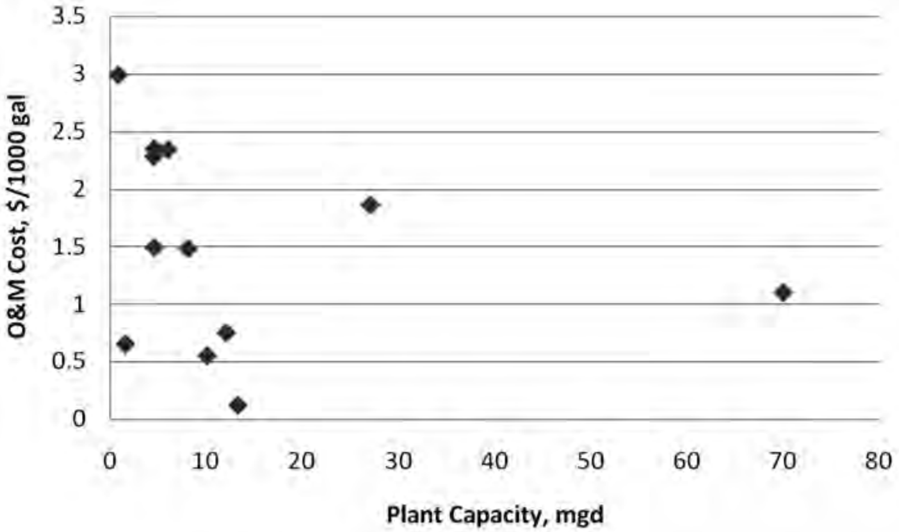


Figure 3.21 Operation and maintenance cost versus plant capacity

facilities, 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 and not specifically post-treatment O&M costs. 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 cost 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

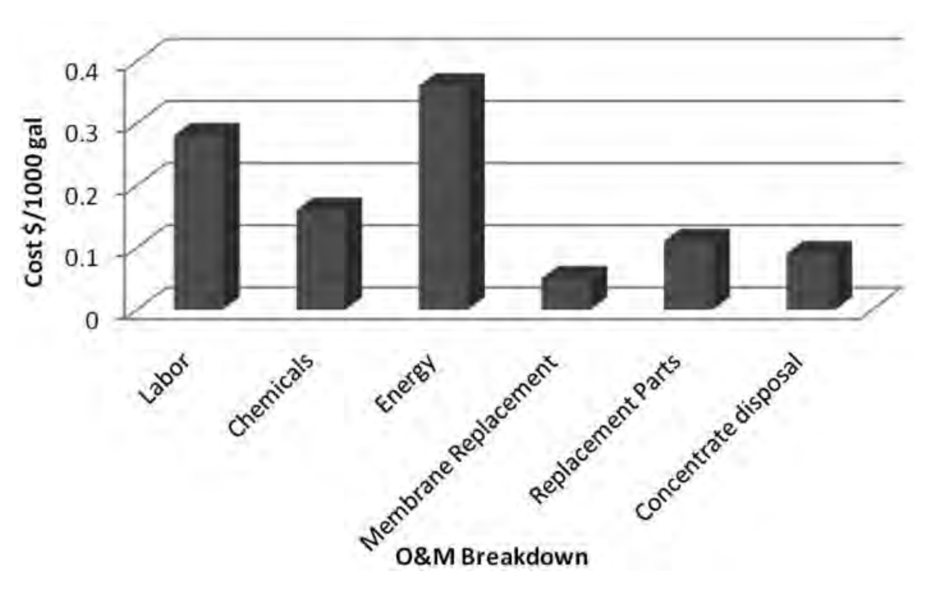


Figure 3.22 Operation and maintenance cost breakdown by cost category

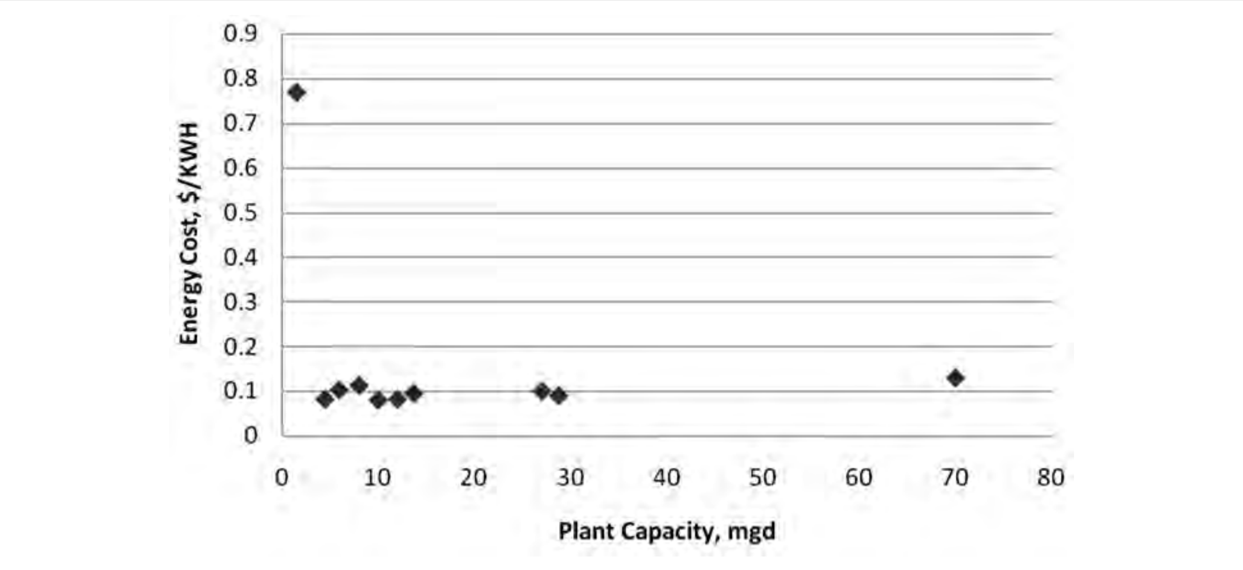


Figure 3.23 Energy cost versus plant capacity

represent changing interest or other impacts on costs over time. A conversion on $1.4132 dollars per euro was used for this calculation.

Figure 3.22 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 are the largest contributors to O&M costs. Figure 3.23 shows the average energy cost for each reporting facility based on the plant capacity. 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.

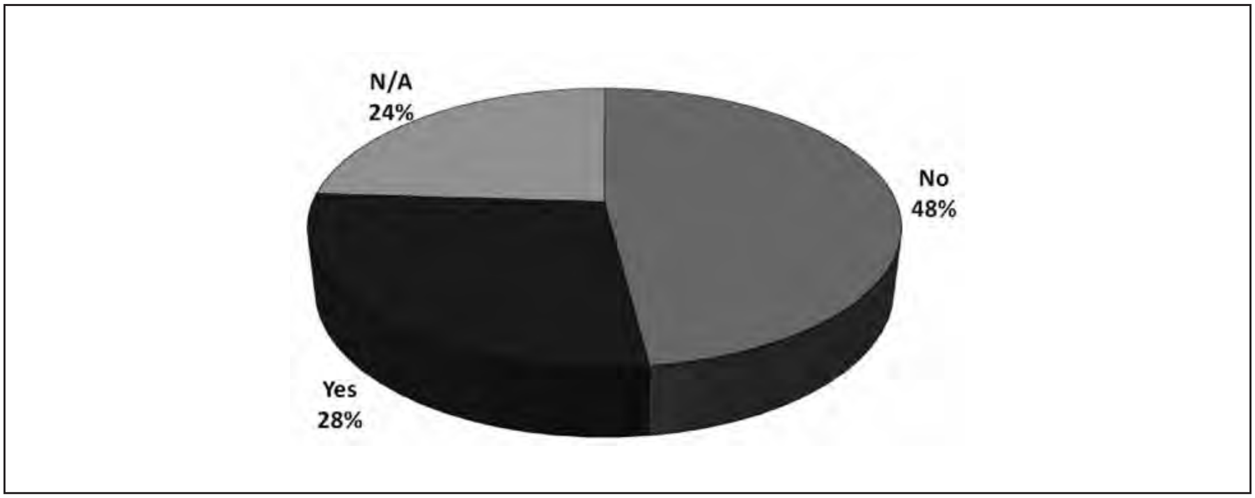


Figure 3.24 Did pilot testing reveal water quality concerns for distribution system?

Section VII: Major Issues and 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. To assist the responder in their efforts, specific topics were identified and presented in order to obtain detailed responses to questions concerning to the following:

- Pilot Testing
- Design of the facility
- Permitting/Regulations
- Facility Startup
- Operations

Respondents were asked to reveal if pilot test showed any water quality concerns for the distribution system. Figure 3.24 shows that forty-eight percent of respondents used pilot testing prior to implementing their desalination, which did not reveal any concerns. Twenty-four percent did not answer the question and twenty-eight percent revealed that pilot testing did reveal information that would be a possible concern for their distribution system. Few water authorities pilot both process and distribution system together.

Respondents noted that pilot testing helped their operation with further understanding issues related to the following:

1. What parameters would be of concern regarding post-treatment stabilization of permeate;
2. Did the design of the degasifier unit help predict the removal of dissolved gases?
3. Were there any blending concerns to be aware of when using a membrane process for salinity or TDS reduction?
4. Did coupon testing help predict corrosion control dosages for sizing chemical feed facility designs?

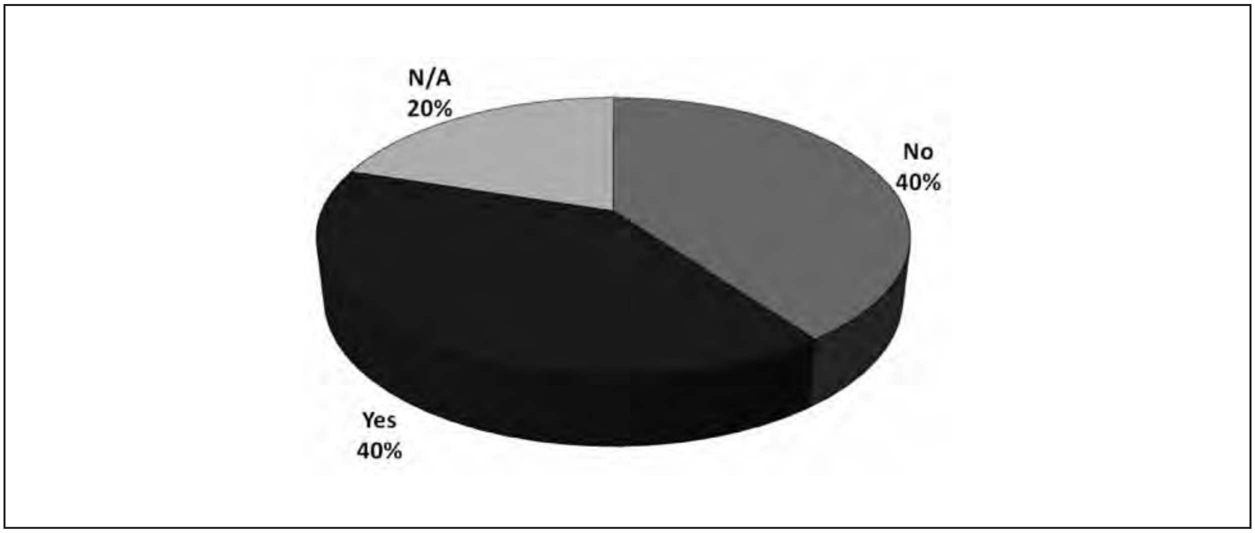


Figure 3.25 Did design of the facility consider impacts of permeate on the distribution system?

Figure 3.25, however, indicated that forty percent of the responders considered the impact of permeate on the drinking water distribution system, hence, indicating that there are many operating utilities that need to be better informed of the benefits of pilot testing and the importance of understanding how the use of membrane processes, particularly desalination, can impact distribution system water quality.

One of the more important lessons identified by the survey was that pilot testing is an effective way to study the full-scale process and in doing so identify possible problems that may occur with the process well before the scheduled plant startup. Data on water quality can be collected and used to develop effective ways for treating water when issues arise with blending, disinfection, and membrane selection. If effective pilot test was taken into consideration, many problems could be identified and responded to, which would minimize future costs required to address the problem after the plant has been placed on-line.

It was noted by one facility that by not considering the design of post-treatment facilities into full consideration, issues with post-treatment would occur. In addition, another facility reported problems after plant start up with clogging of injection wells, and distribution system impacts due to sulfur residuals. Although details were not provided it is important to stress the need to have an effective design that takes into account post-treatment stabilization of permeate.

Another lesson provided by the respondents was related to the design of the intake facility; that is, an adequate and properly designed intake design will reduce potential impacts within the facility. Effective pre-treatment design should also prevent problems with regard to post-treatment of permeate water particularly if by-pass blending is to be practiced.

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. Figure 3.26 shows that twenty percent of the utilities responding to the survey reported that they experienced permitting and regulation issues. Forty percent did not respond to the question and forty percent report that they had not experienced any significant or no permitting issues.

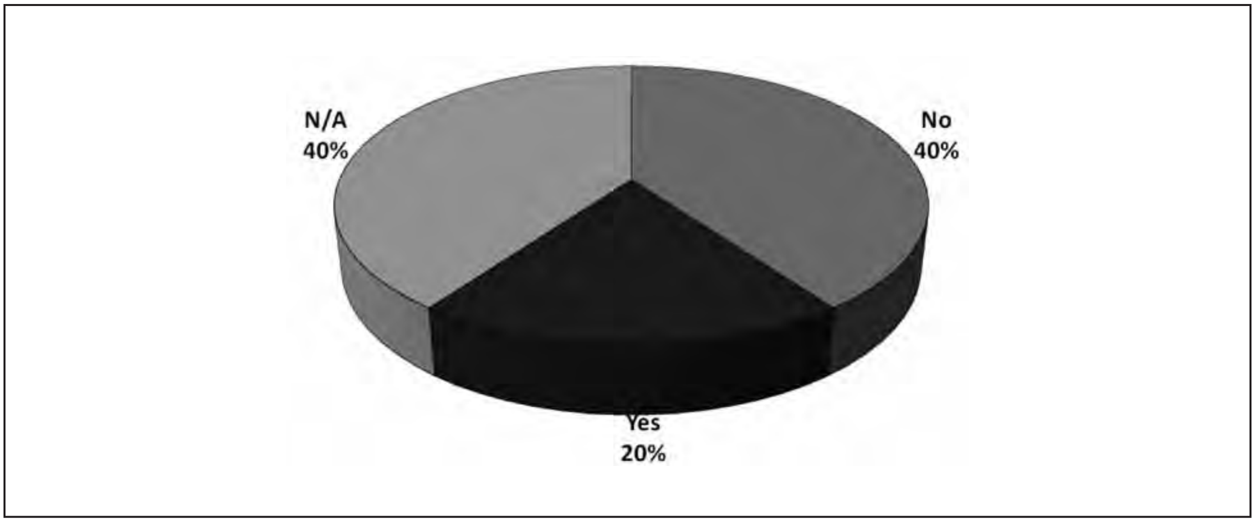


Figure 3.26 With respect to post-treatment (disinfection), were there obstacles to overcome in order to obtain permits/consents?

Specific comments that some of the responding utilities reported included the following issues regarding permitting:

1. A permitting problem due to manganese deposition within the distribution system could be resolved by modifying the operating blend permit and changing operation by simply reducing by-pass blend ratios and preferentially pumping the differing qualities of water to minimize manganese impacts
2. There can be problems in negotiating when citing primary disinfection facilities where chlorine gas is to be used, mainly due to newer storage, safety and bulk storage reporting requirements, and
3. There are a number of testing and permitting obstacles at times when permitting post-treatment and residual process streams that require cooperation, understanding, and time to resolve adequately.

Another theme derived from the lessons learned component of the survey included the concept that careful monitoring of process and water quality is essential in the planning of desalination facilities so that potential impacts of the new system being constructed or supplied will support the environment and reduce potential problems with permitting. For example, selection of an adequate location for the site of a desalination plant should be considered using several factors, most outside the scope of this work. However, it is noted that the desalination plant should be planned on a site in such a manner to allow for the successful implementation and operation of the facility over a long period of time. One respondent mentioned that not having a plant located in close proximity to a residential area would be considered a reasonable choice if expansion is planned in the future for the community.

Plants surveyed were asked to give details about the issues experience in the distribution system upon plant startup and how the identified issue was resolved. As shown in Figure 3.27 forty percent of the plants reported having no significant issues; however, twenty-four percent did not respond and thirty percent reported that they had experienced issues related to the following:

Figure 3.27 Did you experience issues in the distribution system after plant start-up?

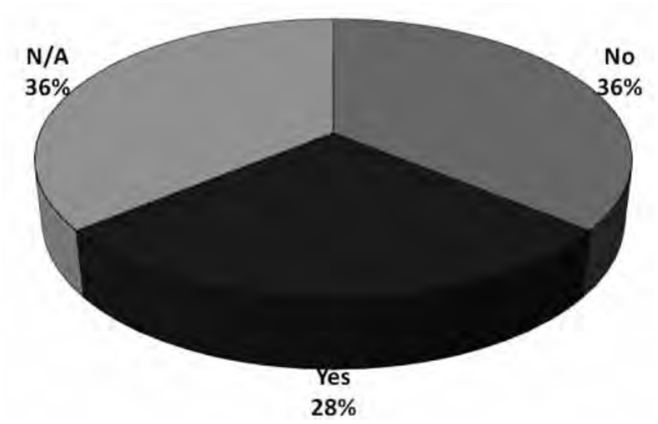


Figure 3.28 Have the identified distribution system issues been directly related back to post-treatment?

1. Manganese precipitation and color, which was resolved by modifying plant operation by the addition of a sequestering chemical in addition to reducing, blend ratios.
2. Warmer water from deep wells had negative impact on customer acceptance, which was resolved by blending the warmer water with cooler water and in doing so also mitigated issues with taste and odor.
3. Failing lead and copper testing at the consumer tap, this was resolved by changing to a different distribution system corrosion control inhibitor.
4. Non-defined corrosion issues with premise plumbing, which was resolved with the use of corrosion control chemical.
5. Injection well fouling (specifically in one case this occurred when a lime system added excess solids to final product which impacted when sent with concentrate into the injection well). This issue was solved by modifying the lime saturator.

Figure 3.28 indicates that twenty-eight percent of the respondents reported issues with operations related to post-treatment facilities. Thirty-six percent did not respond and another thirty six percent reported not having operational issues. Operational issues that were identified included the following:

1. Adequate control of disinfection using chloramines, and
2. Red water issues, which were resolved by the addition of CO_2 to increase alkalinity in the distributed finished water. It was noted that proper and effective pretreatment can reduce problems with post-treatment operations specifically related to disinfection and red water mitigation.

CHAPTER 4
INITIAL WORKSHOP IDENTIFYING UTILITIES' LESSONS LEARNED

INTRODUCTION

An important component of this research project was to conduct an initial workshop involving the participating utilities. The workshop's objectives were to identify practical experiences with post-treatment stabilization, lessons learned, and identify solutions for utilities experiencing issues with post-treatment.

Participants representing utilities from the United States, Caribbean, and Northern Europe attended the expert workshop. Participants had either specific experience with post-treatment of desalinated water or were involved in desalination facilities in the design of post-treatment and operations systems aimed at stabilizing water.

To enhance the quality of the workshop, NWRI was tasked with conducting the experts' workshops using the nominal group technique (NGT). NWRI has a track record of success in the development of technical workshops using the NGT, and was selected as a good way to develop, analyze and rank ideas within a group setting. Using the NGT technique as opposed to a committee style setting allowed for consensus within the group to be reached more rapidly and there is an equal opportunity for presentation of ideas.

WORKSHOP METHODOLOGY

Nominal Group Technique

Originally developed in 1971 as an organizational planning technique, the nominal group technique is a consensus planning tool that helps prioritize issues (Delbecq 1971; Delbecq 1975). Research in group dynamics indicates that more ideas are expressed by individuals working alone but in a group environment than by individuals engaged in a formal group discussion. The NGT is a good way of getting many ideas from a group. It has advantages over the usual committee approach to identifying ideas. Group consensus can be reached faster and participants have equal opportunity to present their ideas.

In the nominal group technique, participants are brought together for a discussion session led by a moderator. After the topic has been presented to session participants and they have had an opportunity to ask questions or briefly discuss the scope of the topic, they are asked to take a few minutes to think about and write down their responses. The session moderator will then ask each participant to read, and elaborate on, one of their responses. These are noted on a flipchart. Once everyone has given a response, participants will be asked for a second or third response, until all of their answers have been noted on flipcharts sheets posted around the room.

Once duplications are eliminated, each response is assigned a letter or number. Session participants are then asked to choose up to 10 responses that they feel are the most important and rank them according to their relative importance. These rankings are collected from all participants, and aggregated. For example, Table 4.1 provides a simple ranking system for three NGT participants evaluating four responses to a problem.

Table 4.1
Example of rankings for NGT

Response	Participant 1	Participant 2	Participant 3	… of importance
A	ranked 1st	ranked 2nd	ranked 2nd	5 = ranked 1st
B	ranked 3rd	ranked 1st	ranked 3rd	7 = ranked 3rd
C	ranked 2nd	ranked 3rd	ranked 1st	6 = ranked 2nd
D	ranked 4th	ranked 4th	ranked 4th	12 = ranked 4th

Sometimes these results are given back to the participants in order to stimulate further discussion, and perhaps a readjustment in the overall rankings assigned to the various responses. This is done only when group consensus regarding the prioritization of issues is important to the overall research or planning project. As its name suggests, the nominal group technique is only "nominally" a group, since the rankings are provided on an individual basis. NGT is based on three fundamental, research-based principles:

1. 'Nominal' groups are thought to generate higher quality ideas than interacting groups typical of classic brainstorming. A nominal group consists of several people (usually gathered in one room) who are prepared to work as a team to resolve a problem. This sharing of ideas (which can be anonymously submitted) promotes a sense of involvement and motivation within the group.
2. The 'round robin' element provides encouragement and equal opportunities for all members to contribute. Contribution from all participants is encouraged and every individual's idea is given equal standing, whether unique or not.
3. Reliable communication requires that the recipient's understanding of a message be checked with the sender, especially in the case of 'new ideas' being put forward. Checks for accurate communication are built in to the technique.

Various forms of the procedure can be undertaken, however, the classical form suggested by Delbecq et al. (1975) uses the following steps:

1. Anonymous generation of ideas in writing begins with the facilitator stating the problem and giving the participants up to 10 minutes to jot down any initial ideas privately. The facilitator also writes down his own ideas.
2. Round-robin recording of ideas allows each person in turn to read out one idea, which the facilitator writes up on a flip chart for all to view and numbered sequentially. This is repeated going around the groups until all ideas are exhausted and any duplicates are eliminated.
3. Serial discussion to clarify ideas and check communication is encouraged by the facilitator. Working through each idea systematically asking for questions or comments with a view to developing a shared understanding of an idea. Discussions are calm and controlled to aid clarification of the idea, they are not heated debates.
4. Preliminary anonymous vote on item importance is usually carried out in the method described under anonymous voting.

5. Further discussion and voting, takes place if the voting is not consistent. Steps three to four can be repeated and any ideas that received votes will be re-discussed for clarification.

As with any technique, there are advantages and disadvantages. NGT is no exception. Some of the obvious advantages are that voting is anonymous, there are opportunities for equal participation of group members, and distractions (communication "noise") inherent in other group methods are minimized. As to disadvantages, opinions may not converge in the voting process and the process may appear to be too mechanical.

Location and Purpose

The workshop was held at UCF's Fairwinds Alumni Center in Orlando, Florida beginning May 21 and ending May 23, 2008. The purpose of the workshop was to identify practical experiences with post-treatment stabilization (i.e., lessons learned) and identify solutions for utilities experiencing problems with post-treatment.

Participants

Attendees of the first workshop included the following persons:

1.	John Countz	Consolidated Water Company, LTD, Cayman Islands
2.	Ian Watson	RosTek Associates, Inc., Tampa, FL
3.	Cesar Lopez, Jr.	San Diego County Water Authority, San Diego, CA
4.	Albert Ilges	AwwaRF, Denver, CO
5.	Donald Baylor	City of Pompano Beach, Pompano Beach, FL
6.	Christine Owen	Tampa Bay Water, Tampa, FL
7.	Gilbert Galjaard	PWN Water Supply Co. North Holland, Netherlands
8.	Paul Jurczak	Town of Jupiter Utilities, Jupiter, FL
9.	Steven Duranceau	UCF Civil & Environmental Engineering, Orlando, FL
10.	Ferne Rico	El Paso Public Water Utilities Services, El Paso, TX
11.	James Harris	Naval Facilities Engineering Command, Norfolk, VA
12.	Carl Spangenberg	Irvine Ranch Water District, Irvine, CA
13.	Sun Liang	MWD of Southern California, Los Angeles, CA
14.	Robert Cheng	Long Beach Water Department, Long Beach, CA

RESULTS AND DISCUSSION

The workshop efforts resulted in the identification of fourteen priority issues associated with the post-treatment of desalinated permeate. Table 4.2 presents the fourteen identified items with their respective topics and are listed in order of importance, based on NGT ranking procedures.

Table 4.2
Outline of priority issues generated from workshop

Priority number	Priority issue
1	"Stabilization" tools for identifying and defining good water quality (consistent water quality) to assure effective water quality results in the distribution system
2	Permeate conditioning/corrosion control
3	Challenges of disinfection by-product formation—post-treatment
4	Blending sources to meet target water quality goals
5	Impacts of blending permeate into existing distribution system
6	Secondary water quality impacts to potable, wastewater, and recycled water
7	Informing (rather than educating) consumers, regulators, and political entities of issues related to desalinated water and its post-treatment
8	Source water characterization as related to finished water quality
9	Permeate conditioning/quality & aesthetics
10	Stabilizing a disinfectant residual
11	Blending for finish water quality
12	Importance of pilot studies specifically focused on desalting pre- and post-treatment.
13	Recognition of water quality aesthetics changes as related to varying water supplies
14	Decisions on pretreatment can affect post-treatment decisions/needs.

"Stabilization" Tools for Identifying and Defining Good Water Quality (Consistent Water Quality) to Ensure Effective Water Quality Results in the Distribution System

The highest ranked priority was related to how utilities should approach post-treatment stabilization with regards to help and available information. The main idea behind priority one is that stabilization of permeate water is a mandatory component of post-treatment for desalination facilities. Consistency of finished water is an important consideration and the utility must be able to define their "consistent" water, because it may hold different results for different utilities and or locations. Utilities should explore and define consistency goals by evaluating how much variation their systems can withstand without experiencing problems in the distribution system, since there is a range of variability that a distribution system can tolerate when integrating desalinated water into an existing water distribution system. Indicators such as the Langelier Saturation Index (LSI), Ryznar, calcium carbonate precipitation potential (CCPP), aggressiveness index (AI), and dissolved inorganic carbon (DIC) are helpful in predicting the behavior of water within a distribution system. It was recognized by the workshop participants that it is important that facilities implement studies and use available "tools" to understand post-treatment challenges in an effort to develop internal management procedures and technical actions; subsequently, by doing so one could provide consistent and stabilized water quality for the distribution system. Suggested tools include pilot studies, distribution water quality modeling, monitoring, coupon studies, linear polarization, and online water quality instruments within the distribution system.

Permeate Conditioning/Corrosion Control

The second highest-ranked priority dealt with permeate conditioning and corrosion control. This topic is interrelated to the highest priority topic identified in the workshop. NF and RO permeate are considered corrosive to many types of materials of construction. The permeate produced by synthetic membrane processes can be "aggressive" water that if not stabilized may cause internal damage to many of the components that make up the water distribution system. The utility is required to understand the interrelated issues between treatment and the distribution system with respect to regulatory compliance, distribution integrity and reliability, and the premise plumbing impacts specifically related to lead and copper release at consumer taps.

Challenges of Disinfection By-Product Formation—Post-Treatment

The third highest priority pertains to the challenges of DBP formation during and following post-treatment operations. Considerations must be made with regard to the type of disinfection(s) used and their potential for DBP formation, whether it be chlorinated, chloraminated, brominated, or iodated species. With regards to pretreatment, the use of pH buffers must be taken into account when it comes to their impact on post-treatment. DBP precursors in bypass water must be considered as a contributor to the total DBP concentration in the distribution system, while providing for inactivation of pathogens. Seasonal changes as well as mixing different water sources in the distribution systems should be known. Utilities must be able to meet regulatory standards for disinfection residuals in the distribution system, MCL's of DBP, and lead and copper levels. Potential health risk and issues with blending are imperative to know. For example bromide in permeate is higher than in blend waters and TOC may be higher in blend waters which can affect DBP formation.

Blending Sources to Meet Target Water Quality Goals

To meet a target potable water quality goal it may be necessary to blend different water sources and is the topic of priority number four. Water utilities will find themselves unable to meet the future demands with a single source. To meet demands, water purveyors will need to diversify their water resources. These new resources will likely vary in finished water quality. The quantity, quality, and economics of source water will influence the appropriate blend ratios for different waters in different seasons.

Impacts of Blending Permeate Into Existing Distribution System

Priority number five relates to the impacts of blending permeate water into an existing distribution system. Blending of newly desalted water supplies in a system having an older infrastructure which historically has been exposed to different supplies of significantly differing quality can cause problems with water quality within the distribution system. Those problems of concern included discolored water, constituents remaining in water such as H_2S, taste, odor, and corrosion.

Secondary Water Quality Impacts to Potable, Wastewater, and Recycled Water

Secondary water quality impacts to potable, wastewater, and recycled systems were identified as priority six. Issues are many, and some were identified. Since regulatory requirements for potable, wastewater, and recycled water differ, utilities are motivated to understand permit limitations that may be imposed by various regulatory agencies. These limitations may impact the use of desalinated supplies if post-treatment does not address conflicting goals that these other permits may represent. For example, conservative ions will increase through each water cycle which will limit reuse and irrigation use. Post-treatment with sodium hydroxide will add sodium to the water supply but a change to the use of potassium hydroxide would reduce the amount of sodium loading into the environment (i.e., changes in sodium adsorption ratio). Another example is the secondary impact of bromide (other unknown conservative ions such as iodide) entering a blended water supply impacting historical DBP speciation and concentrations (reference priority three).

Informing (Rather Than Educating) Consumers, Regulators, and Political Entities of Issues Related to Desalinated Water and Its Post-Treatment

Priority seven topic is "*Informing, rather than educating consumers, regulators and political entities of issues related to desalinated water and its post-treatment*." Although in the NGT process this item was not ranked as a high priority with regards to post-treatment, priority number seven was seen by the participants to be a significant factor if problems with water quality were to occur. Informing consumers, regulators, and political entities of issues relating to desalinated water and its post-treatment is advised. It is also noted that a utilities understanding of its water treatment process, its cost, and benefits is necessary. Post-treatment is necessary to create a desirable water quality for consumers, to meet regulatory requirements, and protect the distribution system and consumer infrastructure. Again understanding water quality and impacts of blending different source waters is imperative.

Source Water Characterization as Related to Finished Water Quality

Source water characterization as related to the finished water quality was ranked as the eighth priority. Finished water quality can be affected by the source water quality fluctuations, negative impacts may occur that will affect water recycling and irrigation. Boron accumulation through the water cycle was given as an example because its accumulation may negatively impact water recycling and irrigation practices.

Permeate Conditioning/Quality and Aesthetics

Priority nine is listed as permeate conditioning, quality, and aesthetics of water quality. NF and RO permeates can contain dissolved gases that may impact the taste and odor acceptability of the water. This is critical for water purveyors in maintaining customer satisfaction and consumer confidence within their drinking water community, within which the utility operates.

Stabilizing a Disinfectant Residual

The tenth-ranked priority considers issues related to stabilizing a disinfectant residual in the distributed water supply. Consideration as to the choice of disinfectants used, types of blending, and regulatory compliance challenges in answering the question "*how to obtain a stable disinfectant residual in the distribution system?*"

Blending for Finish Water Quality

Priority eleven items were related to blending for finished water quality. Currently blending is a term used to explain a specific unit operation. However, there are several classifications of blending related to the post-treatment of blended streams containing NF/RO permeates. It is important evaluate these by the following general classifications:

i. Blending permeate with other sources in a common blending scheme
ii. Bypass blending a component of the raw water into the permeate stream
iii. Blending within distribution system at multiple locations having multiple plants
iv. Conditioning permeate for transport to remote blending or end use locations
v. Treatment of blending bypass or blending mixtures of multiple source waters

Again, this is important because when adding NF/RO permeate sources into a distribution system destabilizing conditions may occur. To mitigate against possible negative effects proper blending is paramount.

Importance of Pilot Studies Specifically Focused on Desalting Pre- and Post-Treatment

Priority twelve notes the importance of pilot studies focused on pre and post-treatment. It may be necessary to continue using pilot plants studies once a facility goes online because it will allow for continued optimization of the process.

Recognition of Water Quality Aesthetics Changes as Related to Varying Water Supplies

Recognizing of water quality aesthetics relating to varying supplies is priority thirteen. Water quality changes will occur when water supply changes, which may generate customer complaints. Utility's knowledge of water qualities can deflect negative responses from consumers.

Decisions on Pretreatment Can Affect Post-Treatment Decisions/Needs

Finally, how pretreatment can affect post-treatment decisions and needs is the topic of priority fourteen. Seawater is vastly different across the globe, so basically what works for one utility does not necessarily work for another utility. For example, in the Cayman Islands the deep seawater from Cayman Trench is rich in hydrogen sulfide yet low in dissolved oxygen. Whereas, in the Bahamas, the raw water contains higher levels of dissolved oxygen in water, the water is warmer and contains 2 to 4 mg/L of hydrogen sulfide. These conditions require careful consideration of compatible construction materials. Similar care should be incorporated into selection of post-treatment materials.

Guidelines for Priority Issues

Upon determination of the fourteen priority issues recommendations were solicited on how to best handle these issues. The recommended actions that can serve as a guide to desalination facilities in handling the priority issues are listed below:

1. Utilities should consider carrying out pilot studies, distribution system water quality modeling, monitoring, coupon studies, linear polarization, and online water quality instrumentations within the distribution system in order to be able to determine if the desalinated water is to be stabilized and how much stabilization is needed prior to introduction into existing or new distribution systems. Through these studies, the utilities will be able to predict a range of operating conditions for the system, which the distribution network can tolerate, while at the same time ensuring that the quality of water supplied is not compromised.
2. For corrosion control, identification of permeate characteristics is necessary. At the very minimum the pH, temperature, alkalinity, ionic strength, hardness, TOC, sulfates, and chlorides of permeate should be monitored. With these data the susceptibility of the distribution system and the internal plumbing of customer premises can be assessed, and the necessary stabilization program can be instituted to mitigate the problems anticipated.
3. When the choice of disinfection has been made, it is recommended that studies be carried out on the formation of disinfection by products. Alternatively, depending on the water source that is being desalinated, the choice on disinfection can be made after conducting studies and assessing if any disinfection by products may potentially be formed.
4. Looking at the target water quality goals, utilities can assess the various sources of water that is available and determine the type of treatment necessary. Blending of different water sources in order to meet the target water quality is a key consideration. The choice of treatment for the different sources of waters will need to be evaluated together with the blending ratios. Using mass balance, various source combinations can be evaluated to meet desired finished water quality, in order to optimize the supply, in terms of cost of production and water quality. An example of this is that utilities can blend different supplies for taste and odor control or blend permeate with bypass water at various stages of the process, for control of TDS and chloride.
5. Impacts of permeate in the distribution systems can be resolved by:
   - Setting permeate water quality goals;
   - Identifying the water quality issues associated with specific source waters and the corresponding permeate water quality;
   - Considering and resolving mixing and stability issues before introducing any new sources;
   - Considering all treatment options to ensure that all drinking water regulations are met; and
   - Developing blending options
6. To resolve the potential issues with secondary water quality impacts i.e., those impact on wastewater and recycled water, it is recommended that utilities understand the comprehensive permit limitations as imposed by regulatory agencies on water, wastewater and water reuse. Knowing the regulatory limits, and the water quality of the available water sources, water quality goals will need to be set that will ensure that all water use, wastewater collection and treatment, and reuse fall within these regulatory limits. The water quality goals will thereafter determine the choice of treatment, blending ratios with multiple sources, quality stabilization and disinfection methods.

7. Customer acceptance is important to the utility and programs need to be introduced to inform stakeholders of the different aspects of desalination and the post-treatment options. Stakeholders must be informed of the reasons for adopting particular treatment; disinfection and stabilization systems and the benefits that they derive as a result of the utilities taking these measures must also be mentioned.
8. Characterizing source water and its variability in terms of quality and quantity during different seasons is important. Utilities will need to factor this, in considering the treatment, disinfection, and post-treatment stabilization options as part of meeting the water quality goals that it is required to meet.
9. Utilities need to understand the quality of water that it produces and take the necessary measures to condition the water to meet the expectations of customers in terms of quality and aesthetics. It is recommended that odor control and taste acceptability tests be conducted, as these are critical customer acceptance indices.
10. To ensure public health, studies need to be carried out on the choice of post-treatment disinfection process and its stability.
11. When blending water from various sources, with and without treatment, are considered, analysis of blend streams and water quality goals are recommended. Such analysis should also include seasonal fluctuations of various sources, varying operating conditions in the treatment plants, seasonal treated water demand patterns, and any hydraulic limitations within the treatment plant and in the distribution systems.
12. Pilot scale studies are recommended to establish pre and post-treatment systems. It is recommended that considerations be given towards the continued operation of pilot scale studies, even after the commissioning of the treatment facilities. Where large-scale desalination facilities are proposed, demonstration scale studies are recommended, over and above the pilot scale studies. In carrying out the studies, utilities should include the storage and distribution systems including any new networks if they are proposed, and simulation of the overall production and supply system ought to be also considered.
13. In order to maintain the aesthetics of water that it supplies, the utility should:
    - Understand water quality differences from different finished water sources.
    - Understand consumers' water quality expectations.
    - Evaluate resultant water quality from potential blend changes—and understand how such changes in blending will affect the aesthetics of water. Flavor, taste, and odor tests are recommended, as these are the primary aesthetic parameters of concern to customers. Such evaluation can serve as a predictor of water quality when changes in blending are necessary for various operational reasons.
    - Institute an action plan for instances when there need to be changes to the water supply. Such action plans should include effective public communication and outreach strategies.
14. As decisions on pretreatment can affect post-treatment options, pilot studies should focus on optimizing the whole plant to meet the pre-determined treated water quality goals, enabling effective post-treatment.

CHAPTER 5
SECOND WORKSHOP ADDRESSING RESEARCH NEEDS

INTENT AND PURPOSE

Another central phase of this research project was to conduct a second workshop involving the participating utilities. This workshop's objectives were to identify research needs to address utilities' issues with post-treatment, and in doing so identify research 'gaps' in order to develop a listing of research needs. Regulations are one of the primary drivers for drinking water research in the United States, and are focused on protecting public health. Because of the use of synthetic membrane processes has continued to increase, the impact of post-treatment operations on distributed water quality where new desalting facilities are placed on-line to augment native water supplies can impact regulatory compliance.

The research identified in this workshop was intended to serve as a starting point for future projects concerning post-treatment. When the research identified in this workshop has been conducted, the findings will provide answers to problems, and in doing so assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits will be realized when the results are implemented at the utility level; consequently, the second workshop primarily consisted of water purveyors who would ultimately be responsible for implementing the identified research topics. Hence, it is important that the majority of the same participants who worked together in conducting the first workshop also attended and worked together in this second expert workshop.

The ultimate purpose of this coordinated workshop effort was to develop a research agenda regarding desalination post-treatment and the secondary impacts the water community is facing when implementing non-traditional treatment processes. The workshop served as a vehicle to discuss research needs aimed at improving the understanding of post-treatment stabilization of desalinated water for municipal drinking water use. Consequently, each of the specific research needs that were identified and evaluated were systematically identified and ranked according to their level of importance.

LOCATION AND SETTING

The workshop was a two-day event, held in southern California, beginning February 9 and ending February 10, 2009. The first day of the workshop was held at the Irvine Ranch Water District's (IRWD's) headquarters in Irvine, California. During this first set of meetings, participants were able to visit IRWD's brackish water RO WTP. The plant site visit allowed for an evaluation of IRWD's post-treatment facilities and newly constructed by-pass blending treatment system for manganese control. The second day of the workshop was held at the Long Beach Water Department's headquarter facilities. A site visit was conducted at the City's seawater NF demonstration facility nearby.

In keeping with the success of the first workshop, NWRI was again tasked with formalizing and conducting the workshop using the nominal group technique (NGT). NWRI has a track record of success in the development of technical workshops using the NGT, and was selected as a good

Table 5.1
Ranking of nine key research needs

Ranking	Research need
1	Chloramine residual stability in permeate water
2	Formation of brominated and iodinated disinfection by products in desalted permeate and its blends
3	Testing protocol for post-treatment of desalinated waters
4	Evaluation of the impact of seawater permeate post-treatment on existing infrastructure
5	Performance of corrosion inhibitors or other stabilization chemicals
6	Studying the effects of blending desalinated seawater permeates with ground and surface water sources on aesthetics and customer satisfaction
7	Software tool development for risk analysis in permeate blending with traditional ground and surface water sources
8	Identifying specific constituents in and possible reactions present from the blending of permeates from groundwater, brackish water and seawater sources
9	Identification of alternative post-treatment methods for removal of hydrogen sulfide

way to develop, analyze and rank ideas within a group setting. Chapter 4 includes a review of the theory and procedure of the NGT.

IDENTIFICATION OF NEEDS

The participating utilities research needs workshop began by answering the question, "*In your opinion, what are the three most important post-treatment research needs today?*" This discussion led to the development of nine key topics identifying the specific research needs for post-treatment. Table 5.1 presents these nine topics that have been ranked in order of importance. Participants were broken up into groups and assigned the identified research needs listed in Table 5.1. These topics were discussed according to the NGT as a way to develop and analyze the research needs.

Chloramine Residual Stability in Permeate Water

This topic was identified as having the greatest priority for further research. A large percentage of utilities use chloramine as a primary disinfectant. However, it has been found that chloramine may not be stable in treated permeate water from a desalination facility. Saline water sources, specifically brackish water or seawater, contain higher concentrations of bromides and iodides. These constituents, notably bromide, can react with and degrade chloramines.

The introduction of desalinated permeate into existing water systems that rely on chloramines for disinfection would adversely impact those water supplies. If the treated permeate water is blended into existing water supplies, the desalinated water may react with and degrade chloramines present in the existing system. Also of consideration are systems that use chlorine for disinfection. These issues present many concerns, one of which is that the disinfectant residual in a distribution system may be reduced or eliminated.

Research is needed to address reported problems with stabilizing chloramine residuals in desalted permeate water. Initially, a literature review should be conducted to determine what the current status is of bromide and iodide studies. It would also be beneficial to perform bench scale work and develop the appropriate analytical methods for bromide and iodide levels. Then, research should be done on ways to reduce bromide and iodide concentrations in desalination permeate. Specifically, ion exchange, chemical precipitation, chemical oxidation and use of a second pass RO process are possible technologies that could accomplish bromide and iodide reduction. Reducing bromide levels would reduce the potential for reactions with chloramine.

In addition, there needs to be an increased understanding of halogen chemistry and its interactions with chloramines. Within halogen chemistry, bromide and bromamines need to be further studied as very little is known about the chemistry of the bromide acceleration of chloramine decay. In order to accomplish the necessary research, a time frame of approximately two years would be necessary. An estimated budget of $450,000 would be required for conduct of this investigation.

Formation of Brominated and Iodinated Disinfection By-Products in Desalted Permeate and Its Blends

The issues of potential formation of brominated and iodinated DBPs in desalted permeate is another key issue identified as requiring further research. The use of desalinated water supplies is relatively new to U.S. public water supply systems, and as a result there still lacks a thorough understanding of this DBP formation resulting from constituents found in seawater and brackish raw water supplies.

Permeate from these sources can contain significant amounts of bromide and iodide. It is unknown how these ions will react when introduced to a distribution system that is coupled with blending and disinfection using chlorination or chloramination. Additional DBPs are likely to be produced when different waters are blended which may become a public health issue. There is a risk when exposing consumers to unregulated and unknown DBPs as their health effects are of unknown significance in long term exposure. Iodinated DBPs have been known to cause taste and odor issues. These compounds are relatively unknown and may have future regulatory importance. With diminishing traditional sources of drinking water, the use of seawater desalination in the United States and abroad will increase. Therefore, this issue will become increasingly important as water suppliers utilize brackish or seawater resources.

It is important to further understand the issues discussed. Initially, research should involve studying the formation of unregulated, halogenated DBPs in disinfected RO permeate water, as well as studying the effects of blending this permeate with other treated water sources. Other treated water sources could include groundwater, groundwater under the direct influence of surface water or surface water that contains natural organic matter. Key concepts would be conditions under which formation will occur at the interface where desalted seawater permeate blends with native or conventional water supplies. An evaluation of the permeate blends should include an examination of chloramine, chlorine or other disinfection requirements and subsequent impacts on these DBPs. Unregulated DBPs would be those suspected to be of health concern and will be selected by the researcher and will include at a minimum brominated and iodinated acetic acids, and brominated and iodinated THMs. The focus should be specific to permeate of desalinated (seawater) facilities that blend with native or conventional supplies to identify the conditions under which these DBPs can form. An understanding of the formation should be used to identify possible strategies for reducing exposure to these chemicals of concern. An estimated time frame of three years would be necessary. Also, a budget of $450,000 would be anticipated.

Testing Protocol for Post-Treatment of Desalinated Waters

As the demand for alternative water sources, such as desalinated water, increases so does the need for a testing protocol for post-treatment of desalinated water. There are many factors associated with distributed desalinated waters and its effects on distribution systems. A testing protocol for post-treatment would aid in addressing these water quality issues. Development of this protocol would give utilities an understanding of corrosion, biological stability, pH and residual stability issues associated with desalinated waters. This protocol would aid utilities in developing post-treatment operations that are appropriate to their water quality issues, and making permeate water more compatible for blending and distribution to existing infrastructure. Failure to address this issue could result in degraded water quality, damage to existing infrastructure, leading to decreased customer confidence, higher replacement costs and added maintenance.

A good approach to develop a testing protocol would be to gather information from utilities serving desalinated waters before and after the introduction of new water sources. Case studies could be complied that have looked at permeate water quality and unit operations and processes that have been used for post-treatment. Samples of distributed desalinated waters should be taken before distribution into existing systems or before blending takes place to see how the water quality has changed because of these factors. A better understanding of effective post-treatment for desalinated water will not only benefit existing treatment plants but will also encourage future use of these particular processes. An estimated time frame necessary to execute this project would be approximately two years and require an estimated budget of $250,000.

Evaluation of the Impact of Seawater Permeate Post-Treatment on Existing Infrastructure

Various pipe materials, such as concrete, iron, copper, and PVC, are used in drinking water distribution systems (McNeill and Edwards, 2001; Boffardi, 1995). Distribution systems differ in age, size, pipe, appurtenance, quality and treatment systems and receive different blends of finished waters depending on where water is taken and how that water is delivered. The effects of changing combinations of different source waters will impact the ability of a water purveyor to distribute consistent high quality water at any given time. Although many studies have focused on the disruption of existing inorganic and organic films on these pipe surfaces and associated appurtenances when exposed to different blends of water, additional work is required to investigate, in a systemic manner, impacts of blending post-treated seawater permeate on existing infrastructure.

The quality of blended water and treated permeate likely will impact the overall corrosivity of the water supply, and methods are needed to evaluate appropriate infrastructure materials of construction. An evaluation of the impact of post treated seawater permeate on existing infrastructure would possibly result in the use of newer alternative materials of construction or delineation of unsuitable existing materials that would need to be removed from service prior to blending or seawater permeate use. An estimated time frame necessary to execute this project would be at least two years. A preliminary budget of approximately $300,000 would be required to conduct this research effort.

Performance of Corrosion Inhibitors or Other Stabilization Chemicals

Corrosion control inhibitors have shown to be of beneficial use for internal corrosion control in drinking water distribution systems, and are often added to water to address issues related to lead and copper corrosivity. The more predominant types of inhibitor used for conditioning include zinc orthophosphate and blended ortho-polyphosphate formulations. Permeate water clearly requires stabilization; however, questions remain regarding effectiveness and performance. Research is needed to address issues regarding measuring the effectiveness of inhibitors, evaluate known testing procedures for chemicals and their effectiveness for permeate conditioning. The testing should be patterned to determine performance, and possibly include jar testing.

The goal of the research is to develop a predictive tool to independently assess manufacturer claims regarding the effectiveness of the product in treating permeate streams for corrosion control. The inhibitors and other stabilizing chemicals included in the study should be evaluated for scale inhibition properties, development of coating films on internal piping surfaces, buffering index capacities, and mechanistic delineations. A time frame of approximately two years will be required and the study will require a funding level of $250,000.

Studying the Effects of Blending Desalinated Seawater Permeates With Ground and Surface Water Sources on Aesthetics and Customer Satisfaction

Little has been studied on the effects of blending desalinated permeates with traditional ground and surface water sources on aesthetics and customer satisfaction. Customers are accustomed to drinking water that comes from traditional or native water sources. Surveys have been performed in the Western United States to determine customers' reactions to permeate water. It has been found that customers' aesthetically prefer water that comes from traditional ground and surface water sources in comparison to desalinated seawater supplies. However, desalinated water sources continues to grow. Research needs to be conducted to better understand what occurs when blending takes place in aged infrastructure and mixed infrastructure appurtenances. In addition, it would be beneficial to determine what factors contribute to the aesthetic differences in permeate and groundwater. Utilities not only have the responsibility of delivering safe drinking water, but also need to maintain customer satisfaction and confidence through the implementation of Consumer Confidence Reports and annual reporting requirements.

In order to address these issues of the aesthetic quality of blended water, research needs to be done in order to better understand the chemistry that occurs in blended waters. This includes simulating various operational scenarios and system configurations. It would be useful to identify specific constituents in the various water sources that can affect the taste, color and odor of permeate water that has been blended with surface water. It is also suggested that different blending methods and blending ratios be examined in order to determine what is best suited for customer satisfaction. In addition, public information programs and communication methods with customers should be employed so as to avoid dissatisfaction and loss of confidence from the public. Research on this issue would approximately take two and a half years with an estimated budget of $300,000.

Software Tool Development for Risk Analysis in Permeate Blending With Traditional Ground and Surface Water Sources

Few software tools exist that analyze the effects of blending permeates with traditional water sources, thus creating a need for the development of additional software resources. The use of permeate water is relatively new to U.S. public water supply systems, and as the need for permeate water sources increases so will the need for a tool to help utilities to understand the possible effects of mixing permeates with existing water sources. Seasonal variations in water quality are common for surface water sources. In addition, water chemistry factors effecting taste, color and odor are specific to each water source and treatment technique employed. These variations effect the permeate water quality, as well as effect blended water quality. Blending permeate water sources without knowledge of the impacts can result in infrastructure damages. Blended water quality can take unexpected turns as water characteristics are specific to each site. Customer satisfaction may also suffer if issues are not addressed.

Software tools that can analyze water quality variation will allow utilities to better predict blending effects with traditional water sources. In order to begin developing software tools that can perform risk analyses for blended permeate and traditional water, representative utilities should be visited. Information on their infrastructure types, materials used, existing treatment processes and local regulations would have to be compiled. Variations in water quality and water chemistry unique to each utility would also have to be studied. All of these factors would have to be combined and related, using modeling, to develop post-treatment software. Also, it would be beneficial for research should be done on blending methods and the number of sources blended.

The approximate time frame for a research project of this nature would be about two years in duration. An anticipated budget of about $400,000 would be necessary to carry out the research and create the software.

Identifying Specific Constituents in and Possible Reactions Present From the Blending of Permeates From Groundwater, Brackish Water, and Seawater Sources

This research need is similar to that discussing blending of desalinated permeate with traditional ground and surface water sources and its effects on aesthetics and customer confidence. However, this topic is designed to specifically address those issues applicable to blending membrane permeate from groundwater, brackish water and seawater sources.

Groundwater containing less than 1000 mg/L TDS is typically treated using NF membrane technology. Water with a TDS concentration of 1000 to 10,000 mg/L is typically treated with brackish water RO membranes. Finally water that has more than 10,000 mg/L TDS is treated using seawater RO membranes. Each of these membrane treatment techniques: NF, brackish water RO, and seawater RO, all produce different permeate with varying levels of water quality. Very little has been studied on the possible effects of blending these water sources. It is proposed that possible problems arising from permeate blends is different than those associated with blending permeate and traditional water sources. Further study is needed to understand the risks involved. As the use of membrane technology expands, blending of various permeate water sources will occur and this may become an issue leading to possible water quality issues, distribution system damage and customer dissatisfaction.

Research to address these issues should include water quality analysis of the different permeate waters. Bench or pilot scale testing should be performed testing different blending scenarios and blend ratios. Chemical analysis of water quality following the several blending scenarios should be done to observe how water quality changes. An approximate time frame for this type of research should take about one year with a budget of $150,000.

Identification of Alternative Post-Treatment Methods for Removal of Hydrogen Sulfide

Feed streams from brackish groundwater, deep seawater intake and some bank seawater intake all contain relatively high amounts of sulfur. Acid addition in the feed stream is common to avoid calcium carbonate scaling in the permeate stream, and permeate pH is commonly between 5.5 and 6.5. While this measure prevents scaling, the acid addition converts dissolved sulfide to gaseous hydrogen sulfide. Neither the conventional pretreatment process (microfiltration, acid, or antiscalant addition) nor the membrane process will remove hydrogen sulfide.

Aeration and oxidation are the two primary means of removing hydrogen sulfide; however, the involved chemical reactions are not well defined, as well as these processes allow for the possible formation of elemental sulfur. Packed tower aeration is another technology often employed to strip hydrogen sulfide from the water. However, scrubbers used in packed towers often clog without proper maintenance and cleaning. If maintenance and cleaning is performed regularly, it becomes very expensive. Off gas as a result of hydrogen sulfide removal is odorous and can be corrosive. Odor and taste issues can cause customer complaints. The corrosiveness of hydrogen sulfide can lead to distribution system damage. Thus, alternative methods for removal of hydrogen sulfide are necessary as membrane treatment of ground and surface water increases.

In order to address the issues with hydrogen sulfide removal, information on all existing technologies used for removal need to be collected, especially for technologies other than scrubbers. Compatibility of these technologies with membrane treatment should be explored. Innovative hydrogen sulfide removal technologies that are compatible with membrane treatment should be applied to water samples taken from utilities that experience the highest levels of hydrogen sulfide. Bench or pilot scale studies should be implemented using the different removal technologies. To complete this research, approximately 12 to 18 months should be allotted with an estimated budget of $100,000.

CHAPTER 6
POST-TREATMENT CASE STUDIES

SELECTION AND CATEGORIZATION

Several of the participant water purveyors were selected to serve as example case studies regarding post-treatment applications. The facilities were grouped by source water as delineated in the questionnaire that had been distributed; seawater (SW), brackish groundwater (BGW), brackish surface water (BSW), and fresh (hard) groundwater (FGW). These few examples are provided to illustrate common issues, such as corrosivity, in addition to specific facility post-treatment issues and related operational challenges. The applications and challenges of post-treatment operations downstream of synthetic membrane process permeate are in many cases unique to each source water. The water purveyors that are highlighted are listed below:

1. Surface water
    - Seawater (SW)
        - Tampa Bay Water Desalination Plant, Florida
        - Governor's Harbour Plant, Cayman Islands
    - Brackish surface water (BSW)
        - The Heemskerk Water Treatment Plant
2. Ground water
    - Brackish groundwater (BGW)
        - The Town of Jupiter Utilities, Florida
        - Irvine Desalter Primary Treatment Plant, California
        - Kay Bailey Hutchison Desalination Plant, Texas
    - Fresh groundwater (FGW)
        - City of Pompano Beach Water Treatment Plant, Florida

Completed participant questionnaires included information on their basic post-treatment operations, disinfection used, post-treatment problems, and water quality data. Information regarding each participants post-treatment operations that had reported in the questionnaire has been condensed and summarized are shown in Table 6.1. Table 6.2 presents average water quality data as reported for permeate and point-of-entry (POE) locations for the highlighted facilities. Additional site specific information was obtained from the participant utility or existing applicable literature.

SEAWATER CASE STUDIES

SW-1: Tampa Bay Water

Description and Highlights

Tampa Bay Water (TBW), owner of the desalination plant, is a large Florida water supply wholesaler, providing drinking water to its member governments: Hillsborough, Pasco and Pinellas counties and the cities of New Port Richey, St. Petersburg and Tampa. Groundwater from aquifers

Table 6.1
Post-treatment information

	Plant name	Sequence of post-treatment operations	Post-treatment problems	Blending or by-pass	pH control	Corrosion control
Surface water	Tampa Bay Water Seawater Desalination Plant	1. CO_2 addition 2. Saturated lime injection 3. Disinfection with free chlorine 4. Blending	Calcium turbidity in finished water.	Seawater permeate blended with treated SFW, blended product is adjusted for pH and alkalinity, and blends with GW	• pH/alkalinity adjustment facility with carbon dioxide and lime addition	• pH adjustment • Alkalinity adjustment • Hardness adjustment • Blending
	Governor’s Harbour Plant (Cayman Islands)	1. pH adjustment 2. Air stripping 3. Caustic addition 4. Calcium hypochlorite disinfection 5. Corrosion inhibitor	• Biogrowth in air stripping towers • Chemical injector plugging	None	• Addition of NaOH (caustic)	• pH adjustment • Corrosion inhibitor
	Water Treatment Plant Heemskerk, Netherlands	1. Alkalinity recovery 2. Blending 3. pH correction; caustic 4. Disinfection	Corrosion of pipeline and appurtenances used to transport desalted permeate to groundwater blending locations	RO permeate is blended with GW supplies.	• Online measurement system • Automated CO_2 or NaOH addition	• pH adjustment • Alkalinity adjustment • Hardness adjustment • GW Blending

(continued)

Table 6.1 (Continued)

	Utility name	Sequence of post-treatment operations	Post-treatment problems	Blending or by-pass	pH control	Corrosion control
Ground water	The Town of Jupiter Utilities, FL	1. pH adjustment 2. Degasification 3. Chlorination 4. Ammonization 5. Blending	• Chemical injector plugging • Corrosion of plant infrastructure between RO and IX blending location	LS, GW and IX water blended with RO permeate. RO process operates as a direct ratio to the IX process.	• Addition of NaOH (caustic) • Blending of RO and IX water as fixed ratio based on flow	• pH adjustment • Hardness adjustment • Blending of RO and IX
	Irvine Desalter Primary Treatment Plant, CA	1. Air Stripping 2. Decarbonation 3. Blending with sequestering agent 4. Caustic addition 5. Disinfection	• Corrosion events • Colored or red water • Manganese precipitation	Post treated desalted finished water blended into Zone 3 distribution system with imported State Water Project and Colorado river aquaduct supplies.	• Decarbonation • Raw water blending (by-pass) • Caustic addition	• pH adjustment • Blending • Manganese sequesterants
	Kay Bailey Hutchison Desalination Plant, TX	1. Blending 2. pH control 3. Disinfection 4. Corrosion control	Concern for distribution system due to moving dynamic interface zones between RO plant's stabilized desalted permeate with the conventionally treated surface water primary supply.	Permeate blended with brackish raw bypass stream.	• Addition of polyortho-phosphate	• Phosphate corrosion inhibitor
	City of Pompano Beach Water Treatment Plant, FL	1. Degasification 2. Caustic addition 3. Corrosion inhibitor addition 4. Blending	Use of lower quality corrosion inhibitor product caused an increase in Pb and Cu; strict specification procedures now enforced.	LS filtered and NF permeate are blended.	• Degasification • pH adjustment • Blending of filter LS and NF permeate • Addition of corrosion inhibitor	• pH adjustment • Orthophosphate corrosion inhibitor • Blending of filtered LS and NF

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.

Table 6.2
Post-treatment water qualities

		Key water quality parameters														
Utility name	Average water quality data	Temp. (°C)	pH	Alk, mg/L as $CaCO_3$	Turbidity, NTU	Conductivity, µmho/cm	TDS, mg/L	Sulfate mg/L	Na, mg/L	Mg mg/L	Ca mg/L	Cl mg/L	Br mg/L	Fe µg/L	Mn µg/L	PO_4, mg/L
Tampa Bay Water Seawater Desalination Plant	Permeate	28	5.5	10	<0.1	500	125	15	60	5	10	160	0.4	<0.1	NR	BDL
	POE	30	7.5	60	1.0	675	350	25	85	12	20	175	NR	NR	NR	NR
Govenor's Harbour Plant (Cayman Islands)	Permeate/ POE	NR	NR	NR	NR	NR	104	6	NR	1.0	70	107	0.40	NR	NR	BDL
Water Treatment Plant Heemskerk	Permeate	10	9.9	44	<0.03	1.3	NR	<0.10	3.96	<0.2	<0.5	3	NR	NR	NR	<0.01
	Blend water	11.6	7.74	186	1.47	75.0	NR	69.2	66.9	10.62	82.3	121	0.22	0.25	0.05	0.06
	POE	11.7	8.1	149	0.07	53.0	NR	43.1	55.5	6.48	50.2	79	NR	<0.01	<0.01	0.06
The Town of Jupiter Utilities	Permeate	22	6.2	25	0.05	400	260	6	70	1.0	3.0	107	0.40	0.03	NR	BDL
	POE	22.8	8.9	36	0.2	450	350	30	35	NR	35	85	NR	0.05	BDL	BDL
Irvine Desalter Primary Treatment Plant	Permeate	27.5	6.75	10.5	0.33	55	16	4	2	0.02	17.35	4.03	NR	0.144	0.24	NR
	Blend water	23.1	7.4	253	0.2	1213	783	229.5	NR	32.2	45.6	130	NR	31.85	92.3	NR
	POE	27.1	8.0	77	0.3	337	191	44.3	57	6.14	17.73	29.8	NR	6.53	19.2	0.15
Kay Bailey Hutchison Desalination Plant	Permeate	21.7	6.75	10.6	1.5	387	180	20.3	67.7	<0.50	<10.0	107	NR	0.040	NR	0.110
	Blend water	21.7	8.04	79.7	0.19	1790	993	80.0	245	19.4	62.1	499	NR	0.044	NR	0.108
	POE	21.6	7.50	24.1	0.17	708	362	14.0	107	4.40	14.9	179	NR	0.056	NR	0.507
City of Pompano Beach Water Treatment Plant	Permeate	25.1	7.51	18	0.13	48	31	NR	NR	NR	NR	NR	NR	NR	NR	NR
	POE	NR	8.9	34	0.32	NR	125	17.5	19.4	2.0	15.6	36.9	NR	0.026	0.003	1.14

POE: Point of entry to distribution system; TDS: Total dissolved solids; TOC: Total organic carbon; TSS: Total suspended solids; BDL: Below detection limit.

and surface water from rivers has been an integral part of Tampa Bay's regional water system, but seawater desalination was selected to add drought-resistance to the region's supply network. When operating at 25 mgd, the desalination plant produces up to 10 percent of Tampa Bay's region's drinking water supply to more than 2.5 million.

TBW's seawater desalination plant has a nominal design capacity of 25 mgd and a maximum capacity of 28.75 mgd. The 8.5 acre site has provisions for future plant expansion to 35 mgd. The main treatment processes include:

- Screening, coagulation, flocculation and contact settling;
- Upflow prefiltration
- Precoat filtration
- Two-pass RO treatment; limited second pass capacity
- Product water conditioning
- Solids treatment including mechanical dewatering
- Chemical storage and feed
- Energy recovery and concentrate discharge systems
- Supervisory Control and Data Acquisition (SCADA) control system.

The plant produces stabilized permeate that is blended into a regional water supply consisting of variable supplies of treated surface, and several groundwater wellfields. Water from the desalination plant is pumped through a 15-mile pipeline to Tampa Bay Water's regional water treatment facility where it is blended with treated surface water. From this location, the blended regional water moves through a 200-mile pipeline where treated groundwater can be added to the supply for delivery to the six governments at more than a dozen delivery connections. Concentrate is diluted with the neighboring power plant's cooling water in up to a 70 to 1 ratio and discharged to Tampa Bay. Figure 6.1 shows a simplified schematic of the complex seawater desalination process along with the blending point of the desalinated water with the treated surface water.

Post-Treatment Issue(s) and Resolutions

Monitoring Water Quality. TBW and its contracted operations group (American Water-Prisidea, Voorhees, N.J; and Acciona Aqua, Madrid Spain) implemented operational controls to produce high quality finished water that met requirements for key parameters turbidity, pH and Langelier Saturation Index (LSI). In addition, the related parameters of temperature, alkalinity, calcium hardness and total dissolved solids (TDS) are measured routinely. Conductivity was used for monitoring TDS as a factor of 0.52 and measured in µS/cm.

The key monitoring parameter for decision making actions was pH measured downstream of TBW's 5-million gallon ground storage tank (GST). The GST was located immediately of two parallel lime contactor units with recarbonation using permeate; the pH prior to the 5-million gallon storage tank served as the primary post-treatment parameter. Ranges for the key parameters were established as follows:

- Turbidity: < 0.8 NTU (daily average, 1.0 as peak value)
- pH: > 7.4 units
- LSI: 0 to +0.5 units (slightly depositing)

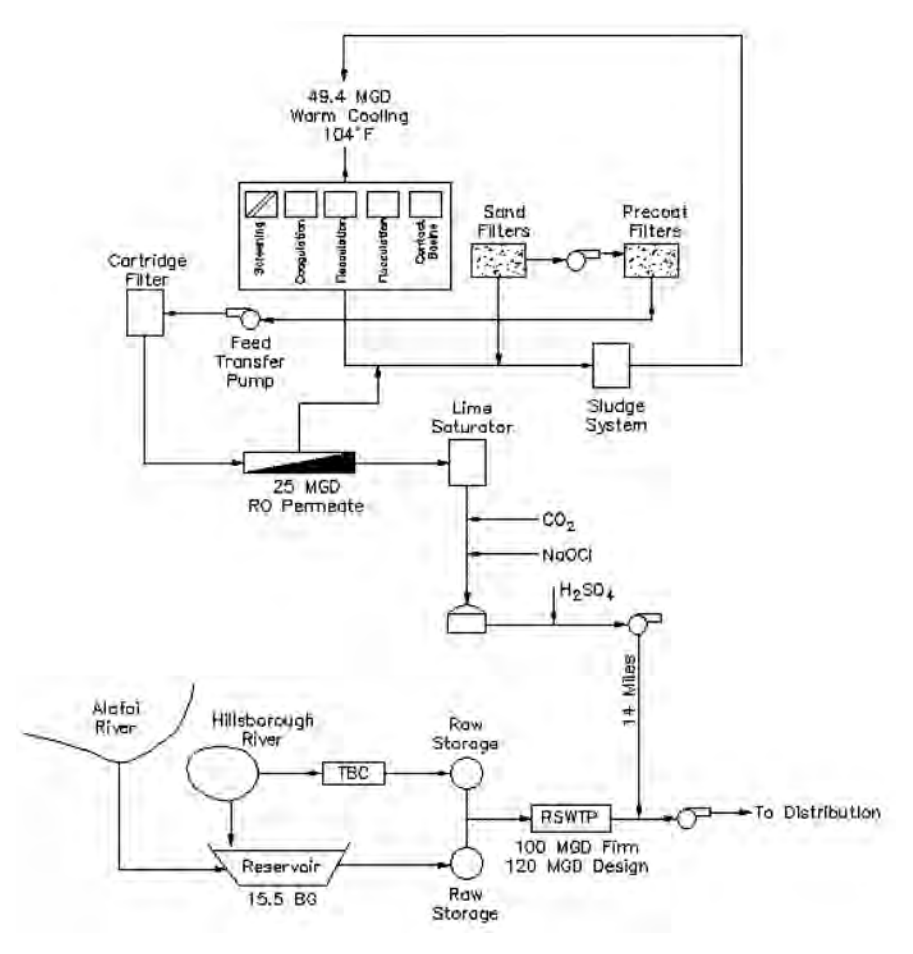


Figure 6.1 Tampa Bay Water process flow diagram

The pH prior to the GST was monitored with the understanding that the value would change in the GST with respect to carbon dioxide dissipation and alkalinity stabilization. Both processes are impacted by changes in water temperature which occur during lime contacting and the subsequent cooling in the GST. Temperature and pH significantly impact turbidity levels; pH had a direct impact on the turbidity such that at pH of 8 units calcium carbonate precipitation would occur and turbidity would increase to higher than 2 NTU; and a temperature change of five degrees Celcius from 35°C to 30°C would alter turbidity from +0.09 to +0.02 at a pH of 7.8 units. The typical target for calcium hardness was then controlled at 80 mg/L as $CaCO_3$. Above 35°C a larger difference between the pH before and after the GST would occur, resulting in the need to incorporate a two-tiered operations approach to control the pH across the GST.

Treatment of Permeate. TBW identified the need to resolve problems associated with demineralized permeate as a result of excessive corrosivity impacts that result. A solution that included addition of lime to the permeate flow was implemented where lime addition to the permeate was controlled by adding to the permeate flow that is fixed for each RO train operating, and is dosed dependent on how many trains are in operation. Carbon dioxide is added as a pre-set condition to match lime dosage based on the number of operating trains, and a controller is used for ongoing adjustments relying on the target pH. Carbon dioxide is dosed at the permeate header, and lime is dosed into the mixing contactors that accepts variable flows from the permeate header, determined by the number of RO trains running. After saturation of the main stream with the lime slurry at the saturators, the lime-saturated water is pumped again into a static mixer. The final chemical added immediately following the contact chamber is sodium hypochlorite for disinfection purposes. Typically the pH obtained in the water sent to the distribution system is 0.2 units higher than the pH entering the GST due to the loss of carbon dioxide (as impacted also by temperature).

Treatment of Blends in Regional System. Tampa Bay Water and Water Research Foundation (WRF) commissioned the University of Central Florida to conduct an investigation regarding corrosion problems in water distribution systems that have historically relied on groundwaters, and are now also being used to distribute water from other sources (Shi and Taylor 2005; Taylor et al. 2005). A pilot plant was constructed using pipes extracted from the existing distribution system. These pipes consisted of polyvinyl chloride (PVC), unlined iron, lined iron, and galvanized iron pipes. The pilot plant blended water from three sources; groundwater (GW), surface water (SW), and desalted seawater solutions (RO). This plant was operated for 2 years and detailed sampling was taken of the various water blends and piping combinations. Iron was released from both unlined cast iron and galvanized iron pipes when the finished water alkalinity was less than the groundwater alkalinity in the blend. The iron was predominantly to be found in the particulate form, which could result in high color. Minor color release was also observed in blends that contained increased levels of sulfates (from treated surface water) or chlorides (from desalted permeate). There was found to be no significant color release from PVC or lined cast iron pipe. It was also determined that copper release increased when groundwater alone was utilized due to high carbonate content. The adverse effects of alkalinity on copper release were mitigated through the use of pH adjustment and/or corrosion inhibitors. It was determined that addition of bicarbonate alkalinity was required to stabilize the blend water within the region and prevent (or at least minimize) many of the problems identified in pipe pilot study. TBW found that these pipe pilot studies were of great benefit in decision making processes.

SW-2: Governor's Harbour Plant, Cayman Islands

Description and Highlights

Consolidated Water Company, Ltd. (CWCO) designs, builds, operates, and in some cases finances seawater reverse osmosis (SWRO) desalination plants and water distribution systems in several Caribbean countries, where the supply of drinking water is scarce and the use of SWRO is economically feasible. CWCO was established in 1973 as a private water utility in Grand Cayman, the largest island in the Cayman Islands group, and obtained its first public utility license in the Cayman Islands in 1979.

CWCO has a total of four separate Design Build Finance Operate and Transfer type water sale agreements currently in operation with Water Authority-Cayman, with a total production capacity of approximately 6.3 million gallons per day, providing 100% of their potable water supply. Consolidated Water Co. Ltd. sells water through retail operations to a variety of residential and commercial customers through a wholly owned subsidiary Cayman Water, which operates under an exclusive license issued to us by the Cayman Islands Government under the Water Production and Supply Law of 1979.

Established in 1998, Cayman Water supplies water to end-users, including residential, commercial and Government customers. Pursuant to the license, CWCO retains the exclusive right to produce potable water and distribute it by pipeline to a licensed service area, which includes the Seven Mile Beach and West Bay areas of Grand Cayman, two of the three most populated areas in the Cayman Islands. The only non-government owned public water utility on Grand Cayman, Cayman Water owns and operates three seawater reverse osmosis desalination plants to supply its retail customers within its licensed service area on Grand Cayman. The Cayman Island desalination plants are located at:

- Bay, West Bay, Grand Cayman
- Abel Castillo Water Works, Governor's Harbour, Grand Cayman
- Britannia, Seven Mile Beach, Grand Cayman

Since the Governor's Harbour and West Bay plants began production of water and the Britannia plant was rebuilt, these plants have consistently been capable of operating at, or near, their rated capacity. As an example, the Governor's Harbour plant was commissioned in January of 1990 and provides water to the west side of the island. Feed water for the RO process is drawn from deep seawater wells with associated pumps at the plant site. The facility maintains an operating recovery of 42 percent with a feed pressure ranging from 880 to 940 psi and produces 1.3 million gallons per day average daily flow. Reject water is discharged into brine wells on the properties at a deeper level than the feed water intakes. A schematic of the process is shown in Figure 6.2.

Post-Treatment Issue(s) and Resolution

Hydrogen Sulfide. CWCO's Cayman water supply originates in the deep Caribbean directly located off the coastline. Although the seawater at the lower levels is high quality, the deep seawater contains on the order of 10 to 25 mg/L of total sulfide. Shallow depths tend to have higher levels of solids, biota and other membrane foulants, hence deeper water was seen to be ideal for CWCO in the Caymans. CWCOhas noted biogrowth in the sulfide stripping degasification towers. Operations has also reported that from time to time, the chemical injectors can experience plugging.

Valve Corrosion. The post-treatment system is unique to Cayman because the entire distribution system is supplied solely desalted seawater; hence blending of desalinated seawater permeate with a native supply is not practiced. The pipeline system in the Cayman Islands covers the Seven Mile Beach and West Bay areas of Grand Cayman and consists of approximately 71 miles of PVC pipeline, with a significant number of accompanying valves. The system appurtenances suffer greatly due to the fact they are iron valves, whereas the distribution system is comprised primarily of PVC pipelines. CWCO documented the corrosion impact of the distributed seawater permeate on standard brass, iron, bronze and cement linings in piping components. The utility also noted plastic embrittlement in its high glass content HDPE and some PVC piping components. To combat these various forms of internal corrosion, CWCO developed and maintains an active valve exercise and replacement programs to minimize the impact of corrosion on water quality and valve functionality. CWCO addresses this historical condition through the replacement of its' older metallic valve materials of construction with EPDM coated valve components.

Storage Tanks and Appurtenances. Alkalinity recovery and sulfide control are critical post-treatment strategies for the seawater-dependent water purveyor. Glass-lined storage tanks are

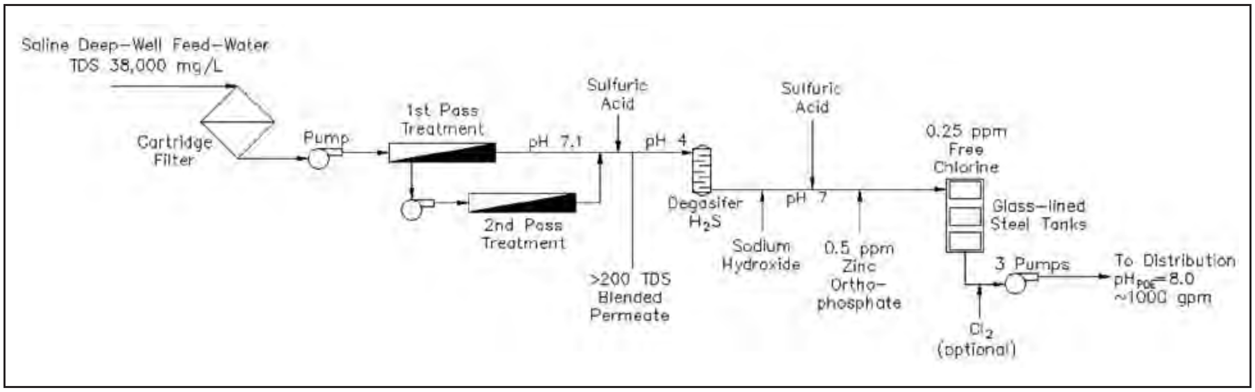


Figure 6.2 Cayman Islands process flow diagram

utilized for dealing with the problems associated with the severity of the corrosivity of this water supply.

Power and Energy. Typically, the energy required is about 2.8–3.5 kWh per cubic meter or 11.0–13.5 kWh per US kilo-gallons. There is a demonstration project underway in the U.S. where they anticipate dropping energy to 1.7 kWh. The overall unit cost for desalinated water has dropped significantly in the last 10 years, and continues to drop as the technology is developed to increase efficiencies and recovery rates. Electricity to CWCO plants is supplied by Caribbean Utilities Co. Ltd. ("CUC"), a publicly traded utility company. CWCO maintain diesel driven, standby generators at all three plant sites from which potable water is pumped to distribution pipelines. During any temporary interruptions in electricity supply, these generators provide sufficient capacity to operate the distribution pumps and other essential equipment, but not the reverse osmosis desalination equipment. In the event of an emergency, the distribution system is connected to the distribution system of the Water Authority-Cayman.

BRACKISH SURFACE WATER CASE STUDIES

BSW-1: Heemskerk Water Treatment Plant

Description and Highlights

N.V. PWN Water Supply Company North Holland (PWN) produces an average of 50 mgd (65 Mm^3/year) of drinking water. At treatment plant Andijk, 20 mgd (25 Mm^3/year) of water from the IJssel Lake was treated for use as drinking water by conventional treatment. The additional 30 mgd (40 Mm^3/year) was produced at the water treatment plants Bergen and Wim Mensink, using conventional groundwater treatment; the water sources were pretreated river Rhine water (from water pretreatment station Cornelis Biemond, WRK I/II) and water from the Ijssel Lake (from water pretreatment station Prinses Juliana, WRK III) that was infiltrated into the surrounding dunes.

In order to increase production capacity with an additional 13 mgd (18 Mm^3/year), PWN constructed the water treatment plant Heemskerk. Since November 1999, pretreated water from the Ijssel Lake (WRK III) has been treated there by an integrated membrane system (IMS) based on ultrafiltration (UF) and RO. Initially coagulation, sedimentation and filtration (CSF) were studied as RO pretreatment; however, nembranes had to be cleaned every 400 h. By CSF/UF pretreatment a much better RO feed quality was obtained. With CSF-pretreated feed water initially UF performance was very good. In periods of algae bloom enhanced backwash with hydrogen peroxide was insufficient and had to be replaced by sodium hypochlorite backwash.

On long term adsorption of macromolecular organics, i.e., coagulant aids may cause permanent fouling. Therefore in the full-scale application GAC filtration is applied to the UF-feed. The Heemskerk WTP has been operating for many years having demonstrated that the system performance is excellent, quality objectives are achieved and membrane integrity is satisfying, and post-treatment efforts have been successful. The direct surface water treatment plant based on the combined application of ultrafiltration and reverse osmosis has the following quality control objectives:

- Removal of pathogenic micro-organisms;
- Removal of organic micropollutants e.g., pesticides;
- Removal of inorganics (chloride, sodium, sulfate, hardness);
- Biological stability.

Reverse osmosis was chosen as the barrier against the identified or suspected trace pollutants.

Post-Treatment Issue(s) and Resolution

Control of Blending Operation. The RO permeate from the UF/RO plant was found to be corrosive during initial transfer in a dedicated pipeline. To combat the corrosivity problems, the RO permeate was blended with water from the nearby Bergen conventional water treatment plant in a ratio that fixed total hardness of 1.5 mmol/L as Calcium. The amount of permeate that remained was transported towards the Mensink water plant and blended. The hardness after blending at Mensink was fixed to 1.5 mmol/L as Calcium, yet because there is less filtrate available to effectively blend to the total amount of groundwater available, the hardness of the groundwater is controlled by pellet softening. To condition the filtrate for transport to the blending clearwells of the Bergen and Mensink water plants, the permeate was conditioned to a slightly positive Langelier Saturation Index by increasing the total inorganic carbon (TIC) concentration through the addition of carbon dioxide followed by sodium hydroxide.

Biological Stability. Biofilm monitoring was applied for assessing the biological stability of the product. The adenosine triphosphate (ATP) content on the biofilm rings in the monitor was low. The biofilm formation potential (BFR) was also low (<2 pg ATP/m^2-day), and the iron and manganese accumulation rates were below detection limits (<0.002 and <0.0004 mg/ft^2-day, respectively). The RO product, assimilable organic carbon (AOC) concentration and BFR were low, 0.03 mg/L Ac-C eq and < 0.03pg ATP/cm^2-day, respectively, indicating a high degree of biostability.The biological stability of the blended product is dependent on the biological stability of the conventionally treated water.

BRACKISH GROUNDWATER CASE STUDIES

BGW-1: Town of Jupiter Utilities, Florida

Description and Highlights

The Town of Jupiter Water Utilities (Jupiter) own and operates membrane desalination drinking water infrastructure that first came on-line in December of 1990. The facilities are located at 17403 Central Boulevard in Jupiter, Florida. Jupiter serves approximately 80,000 residents of Northern Palm Beach and Southern Martin Counties on the east coast of Florida. The area receives nearly 65 inches of rainfall per year; however the majority of this rainfall runs off to tide. The primary source of fresh water supply to this region of Florida is a shallow aquifer located approximately 150 feet below the ground surface. Jupiter is currently operating this site at 13.7 million gallons per day (MGD) as a brackish groundwater Reverse Osmosis plant, and a 13.5 MGD lime softening plant, together with a 1.8 MGD ion exchange system, which removes organics from a shallow groundwater side stream for reduction of the THM and HAA formation potential. The plant has an operating recovery rate of 75 percent. Ultimate potable water demands of Jupiter's service area are projected to exceed 30 MGD while regulators have determined that the safe yield from the local aquifer to be only 20 MGD. Therefore, to meet the demands of growth Jupiter needs to look to alternative water supplies.

Post-Treatment Issue(s) and Resolution

Retiring of Lime Softening Process. The Town will be operating a combination of reverse osmosis, ion-exchange and nanofiltration in the near future, upon which, the Town's reliance on lime softening will come to an end as the lime softening process will be retired from service and the new nanofiltration facility is placed into permanent operation. A change from the older lime softening technology to a state-of-the art nanofiltration technology will provide enhanced water quality to the consuming public served within the Town's service area; however, the change in treatment may cause subtle changes in water quality that may have a secondary impact on corrosion control, and hence, the Town's ability to comply with the provisions of the Safe Drinking Water Act (SDWA) Lead and Copper Rule (LCR) and subsequent disinfection requirements. The Town implemented a blending pilot study to evaluate these changes.

Stability. Jupiter implemented significant upgrades to its water utilities in order to meet many of the challenges of the SDWA. To prepare for the transition, the Town piloted for several years single-element and pilot scale studies that focused primarily on the membrane process and pretreatment. The study represents a typical action that a water purveyor would perform when a new membrane treatment plant is integrated into the existing water community. As would be expected, the Town did not include adequate consideration of post-treatment at the time the process design was vetted with a pilot study. However, during the study the Town found that the high quality permeate from the membrane processes (existing reverse osmosis and new nanofiltration facilities) was chemically unstable. Hence the Town performed a series of jar tests that were used to determine blend ratios and provide process stream flow integration of the old and new facilities. Analysis for hardness, pH, temperature, conductivity and total dissolved solids were among the many parameters evaluated and used to establish the Town's new operational goal to achieve a specific water quality. The Town vetted the jar testing information by conducting pilot scale study using pipe loop

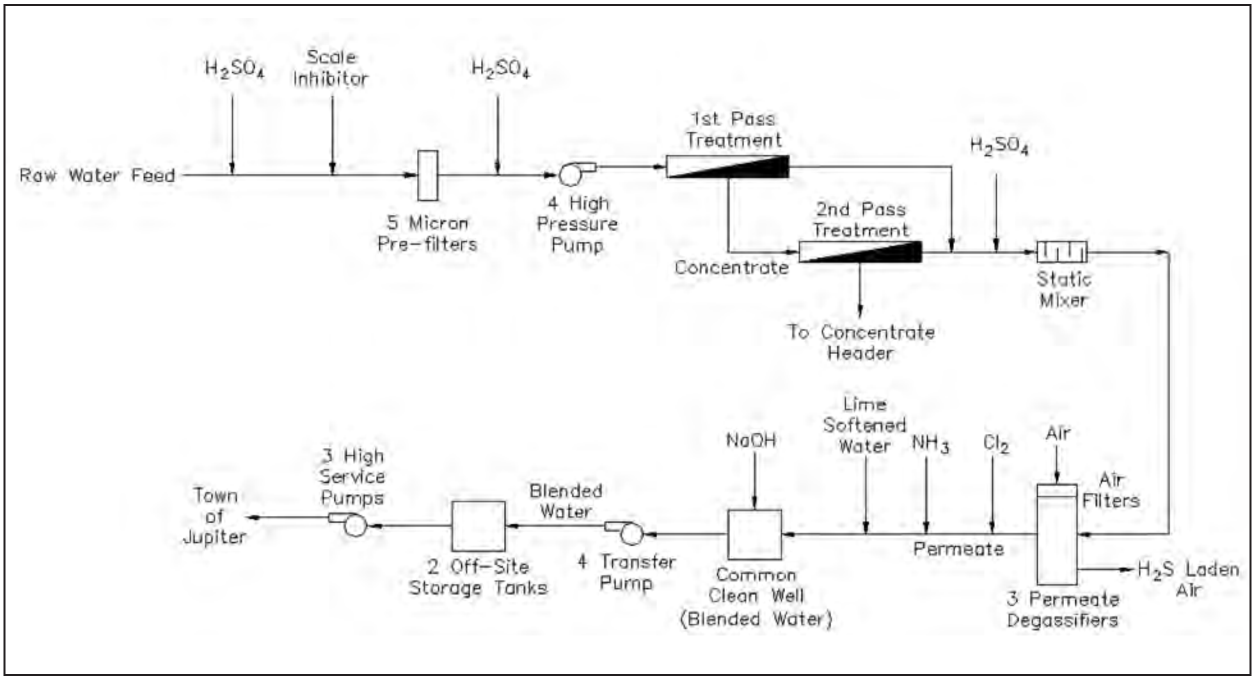


Figure 6.3 Town of Jupiter flow diagram

corrosion testing racks to evaluate possible secondary impacts simulating the integration of their new NF into the existing RO and IX facilities. Because the Town had concerns regarding customer acceptability of the new water blend as compared to the historically produced, the corrosion test rack included a design for the use of coupons, linear polarization probes, and a dishwater component. The dishwasher was included in the study as a qualitative tool to evaluate secondary impacts based on the presence or absence of water spots on fine glassware. Additional evaluations were conducted to determine the required chemical dosages required to provide water slightly positive with respect to Langelier's Index, and a target pH slightly lower than previously operated.

Operational Modifications. Figure 6.3 shows a flow diagram depicting the current sequence of unit operations established as the Town's water plant campus. Jupiter currently utilizes post-treatment with air stripping, caustic chemical addition and blending. The Town has reported post-treatment problems such as chemical injector plugging and corrosion events. Reliable operation at a minimal cost is of course the ultimate goal for the Town of Jupiter. The primary area of concern for Jupiter is fouling; including scaling, plugging, adsorption and biological growth. Table 6.3 and Table 6.4 depicts the target operating conditions with respect to flow rates of nanofiltration, reverse osmosis and ion exchanges. These tables present the "desired" operating flow rates. The pH in Table 6.4 will be adjusted following the water treatment process in the clear wells. The tables also present predicted mathematical values for post-treatment parameters.

BGW-2: Irvine Desalter Primary Treatment Plant (IRWD)

Description and Highlights

Due to natural geology in the area, the groundwater beneath Irvine, California is higher in salts. In 1985, the aquifer was found to contain trichloroethylene (TCE), hence polluting

Table 6.3
Town of Jupiter operation of nanofiltration, reverse osmosis, and ion exchange water treatment facilities

Nanofiltration trains on	Reverse osmosis/ion exchange trains on	Nano permeate flow (MGD)	RO permeate flow (MGD)	Ion exchange product flow (MGD)	Total product flow (MGD)	Calcium hardness (mg/L as $CaCO_3$)	Total alkalinity (mg/L)
1	2	2.90	3.00	0.23	6.35	104	108
2	3	5.80	4.50	0.45	10.98	114	115
3	4	8.70	6.00	0.68	15.60	118	118
4	5	11.60	7.50	0.90	20.23	120	119
5	6	14.50	9.00	1.13	24.85	122	120

Table 6.4
Town of Jupiter operation of nanofiltration, reverse osmosis, and ion exchange water treatment facilities

Nanofiltration trains on	Reverse osmosis/ ion exchange trains on	pH	Conductivity (μmhos/cm)	Chloride (mg/L)	Sulfate (mg/L)	Total organic carbon (mg/L)	Color, CU
1	2	7.0	485	119	6.6	0.45	0.16
2	3	7.0	481	112	6.4	0.40	0.16
3	4	7.1	480	109	6.3	0.38	0.15
4	5	7.1	479	107	6.3	0.37	0.15
5	6	7.1	479	106	6.2	0.37	0.15

groundwater in the area beneath the former El Toro Marine Base. TCE was a solvent used to degrease airplane parts. Groundwater monitoring showed that a “plume” of TCE-tainted groundwater was moving off of the base and toward the main groundwater basin that supplies water for central and northern Orange County, California. In order to utilize this resource, IRWD was required to pump from wells located safely outside the area of the TCE contamination. These wells outside the impacted TCE area are further treated at the Irvine Desalting Plant, which relies on using reverse osmosis, decarbonation and disinfection for potable water production. A schematic of the water treatment process is depicted in Figure 6.4. The resulting purified water supplies enough drinking water each year for about 50,000 people.

The heart of the Irvine Desalter Potable Treatment Facility consists of two reverse osmosis trains. These are used to separate the salt from the water. A total of 434 reverse osmosis membrane elements are inside the 62 pressure vessels. Two 300 horsepower pumps pressurize the water for the membrane separation process. The two trains combined produce 2.7 million gallons per day of desalted water. High quality water from the reverse osmosis process is further treated using a forced air decarbonator. The decarbonation removes carbon dioxide from the water prior to blending this with local well water. Three-inch diameter plastic media are loaded inside the decarbonator to aid in the removal of carbon dioxide gas. A 7.5 horsepower fan blows air through the water, removing carbon dioxide in the process.

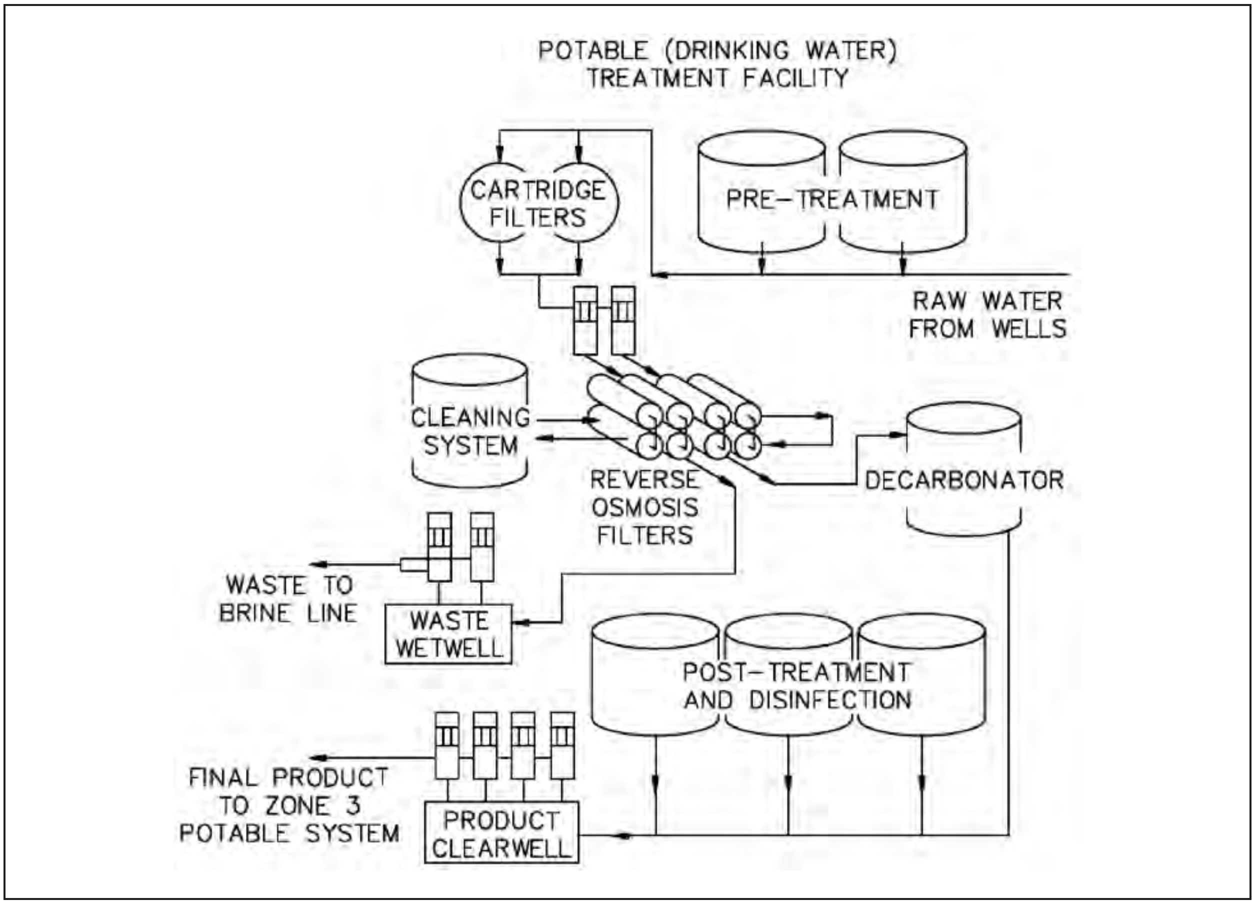


Figure 6.4 Irvine Ranch flow diagram

Post-Treatment Issue(s) and Resolution

Bypass Blending. During the implementation of IRWD's Irvine Desalter Project (IDP), the District had to respond to an unintended consequence of utilizing source water for bypass blending. As was identified by the participant utilities during the lessons learned workshop, blending can improve the stability of the product water by increasing the alkalinity and calcium in permeate to reduce the corrosiveness of the water. IRWD relied on this strategy and intended to use a portion of its RO plant source water used for the reverse osmosis process or from another source. The District's use of bypass blending was to reduce the stress on the membrane system, as it reduces the amount of water that needs to be treated, and thereby reduces the operating costs of the system.

Manganese in Water Supply. After the Irvine Desalter Potable Treatment Plant became operational in 2007, higher than anticipated concentrations of manganese began appearing in the source water to this facility. Because a portion of this incoming flow bypasses the Plant's reverse osmosis treatment process, high concentrations of manganese was found in the product (finished) water. The design criteria for IRWD's RO plant were originally established based on historic groundwater quality information. Water quality testing during startup showed that the manganese levels were higher than anticipated, and that flow rate from each well had also changed. Under these conditions, the product water from the plant contained manganese concentrations that exceeded the Department of Public Health's secondary standard of 50 µg/L manganese concentrations. The

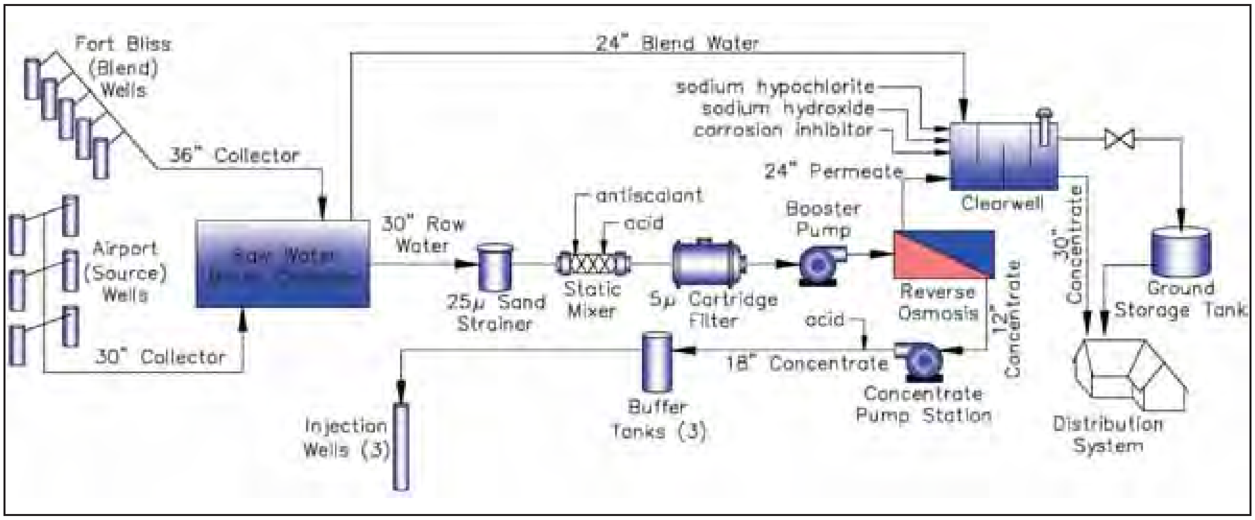


Figure 6.5 Kay Bailey Hutchison water treatment flow diagram

manganese found in the IDP Potable Treatment Plant product water did not create health concerns, but did cause some discoloration of the potable water in the surrounding community. The manganese also caused sufficient discoloration of some control instrumentation at the treatment plant, which necessitated a daily cleaning of some instruments.

Upon detection, IRWD immediately flushed the domestic water system in the impacted area to address color concerns resulting from the manganese. IRWD also took other measures including adding chemicals to sequester the manganese and operating the IDP Potable Treatment Plant at reduced flows. IRWD determined that a manganese removal system was required to reduce manganese concentrations to an acceptable level and fully resolve this issue. The additional bypass treatment filters were constructed in 2008, and successfully placed into operation without incident. Since the bypass treatment was placed into service no complaints or problems have been identified. This significance of this project demonstrates the importance of bypass treatment when using for blending around RO plants.

BGW-3: Kay Bailey Hutchison Desalination Plant

Description and Highlights

The Kay Bailey Hutchison Desalination plant is North America's largest inland desalination facility. A process flow diagram of the facility is depicted in Figure 6.5. It is located on the United States-Mexico border where drinking water supplies are scarce. El Paso Water Utilities and the U.S. Army at Fort Bliss have tapped brackish water reserves beneath the desert floor to stock the 27.5 million-gallon-per-day (mgd) Kay Bailey Hutchison desalination facilities. The project, developed through a public-private partnership involving the Department of Defense and the utility, provides a new source of water to the area and is used to supplement fresh groundwater supplies when the Rio Grande proves inadequate during droughts. It also is needed to protect El Paso's and Ft. Bliss' fresh groundwater supplies from brackish water intrusion. El Paso draws some of its water from the Hueco Bolson aquifer, as do other nearby communities, but the amount of brackish water in the Hueco Bolson exceeds the amount of potable water by approximately 600 percent. To tap into that supply, the city contracted for a facility that would treat and deliver the water using two-stage reverse osmosis membrane desalination process.

Post-Treatment Issue(s) and Resolution

Water Interfaces in the Distribution System. The Kay Bailey Hutchinson desalting plant produces high quality permeate that is post treated for pH control, disinfection and corrosion control. The water produced at the desalination plant is distributed to the water system, and has averaged 3 mgd. As the RO production is gradually increased to 27.5 mgd, there is concern regarding the potential for a moving dynamic (variable) interface zone(s) between the RO plant's stabilized desalted permeate and the conventionally treated surface water primary supply. The water purveyor actively participates in public outreach and program interactions to address quality perception with respect to deterioration and actual overall performance in the distribution system as the facility increases production levels.

Concentrate. Disposal of the facility's 3-mgd waste concentrate, made up of salts and other pollutants, was challenging, though, because the plant is too far inland to discharge waste flows to the ocean. So, designers chose deep-well injection in which concentrate produced by the treatment process is pumped 22 miles across a buried pipeline in the desert to a remote area of Fort Bliss property. Three solar-powered injection wells convey the concentrate 4,000 feet below ground with enough capacity for the next 50 years.

FRESH GROUNDWATER CASE STUDY

FGW-1: City of Pompano Beach Water Treatment Plant

Description and Highlights

The city of Pompano Beach, Florida, covers 22.15 square miles where 7.22 percent of the area consists of open water As of 2007, the U.S. Census Bureau estimated the city's population was 102,745 having a population density of 3,804 per square mile. Like most cities in South Florida, Pompano Beach draws its water from the Biscayne Aquifer. This aquifer is an underground geologic formation where water is stored. This aquifer extends from a few feet to approximately 200 feet below the land surface. The water is pumped from the aquifer to the land surface at two wellfield sites and is transported to the water treatment plant. At the plant, the water is treated with both membrane softening (nanofiltration) and lime softening filtration, fluoridated and disinfected prior to entering the water distribution system. The membrane softening or nanofiltration process has been illustrated with a process flow diagram shown in Figure 6.6. The distribution system consists of over 274 miles of pipe, a one million gallon storage tank and thousands of valves. This network provides the means for the drinking water to reach each customer's property. Continual maintenance of this system such as pipe and valve replacements, and routine flushing of water through fire hydrants, helps to ensure that water reaching the consumer is safe to drink after traveling through miles of pipe.

The City added a 10 MGD nanofiltration membrane facility to soften the raw water and supplement the city's existing lime softening filtration process historically used to produce drinking water. The nanofiltration plant maintains an 85% water recovery rate. The plant does not only

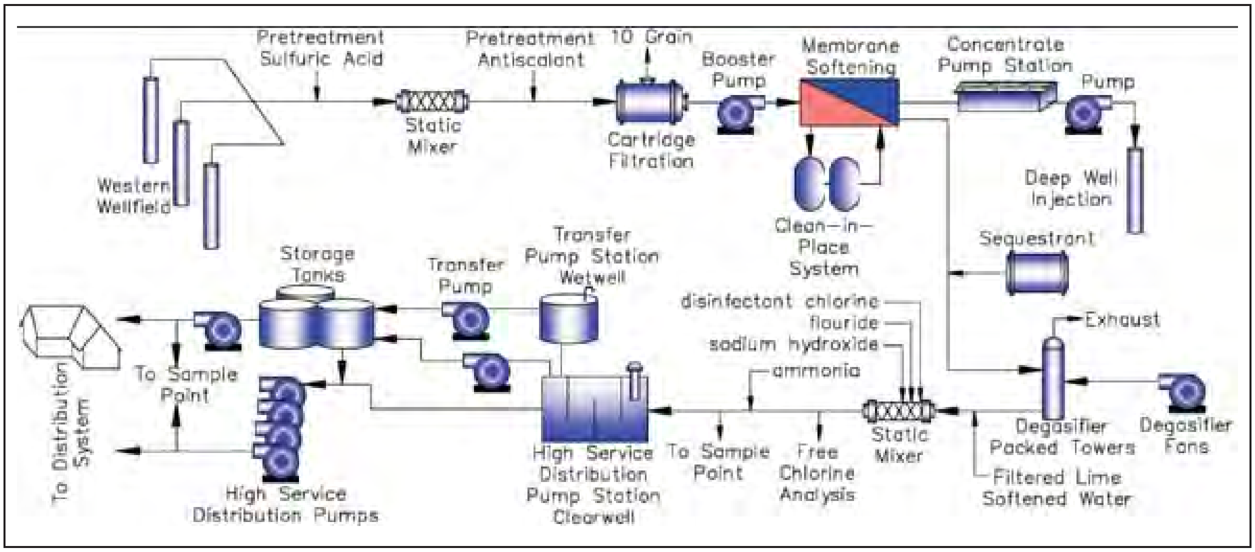


Figure 6.6 City of Pompano Beach water treatment flow diagram

remove hardness, caused by the salts of calcium and magnesium, but also organic compounds, color, bacteria and viruses.

Post-Treatment Issue(s) and Resolution

Blending, Corrosion Inhibitors, and Corrosion Control. Overall the water is of high quality with respect to calcium alkalinity content. Temperatures remain higher than national averages, as would be expected in a Florida coastal community. Higher temperatures generally increase corrosion rates. It is noted that the conductivity is relatively constant and low (<300 µmho/cm at 25°C). Permeate water from the membrane process is further treated by addition of a corrosion inhibitor prior to degasification followed by caustic addition prior to blending with filtered lime softened water in two common clearwells. The city had issues with control of the blending prior to pumping into the distribution system. Use of lower quality corrosion inhibitor product caused an increase in lead and copper content at consumers taps, causing the city to fail a round of LCR monitoring for lead. A chemical selection process with strict specification and procedures was developed and a higher quality chemical corrosion control blended phosphate product resolved compliance issues. The city had not fully considered the impact of permeate on the city's distribution system.

CHAPTER 7
DISCUSSION

WATER QUALITY AND CONSUMERS

Communities throughout the United States and its territories face a variety of environmental infrastructure challenges, not the least of which is the U.S. Environmental Protection Agency's (EPA's) Safe Drinking Water Act (SDWA). Continuing advances in regulatory mandates and increasing demands related to aesthetic criteria for consumer water quality have driven the water community to seek new water supplies and treatment technologies that meet these criteria. Foremost among regulatory constraints are disinfection requirements, disinfection by-product formation and corrosion control regulations. Consumers have become aware of regulatory violation through mandated public notification and Consumer Confidence Reports (CCR), and they have always been aware of the appearance, taste and odor of drinking water. Increasing demands for additional water resources have required communities to seek alternative water supplies that may produce process streams that are not compatible with existing supplies. Potential water quality impacts of particular importance when addressing water quality compatibility involve: regulatory compliance, health effects, the chemicals used to provide disinfection and the factors affecting the corrosiveness of the water distributed to customers.

COMMUNITY WATER QUALITY GOALS

Water purveyors should establish and adhere to community water quality goals including performance objectives regarding the operation of a water distribution system, as water quality goals are important for successful consumer confidence. This is particularly the case when new unit operations and processes adversely alter water quality and public perception (i.e., taste and odor) upon integration into existing water distribution infrastructure. Consideration of the probability of adverse impacts and the identification of the degree of risk (relative) for each regulated water quality parameter should be evaluated prior to integrating advanced water treatment technologies producing high-quality waters into existing (older) water distribution systems. Through continuous refinement of disinfection and corrosion control, utilities can establish corrosion optimization when they embrace programs that address permeate blending issue (i.e., maintaining a non-corrosive non-offensive environment within its distribution system) while controlling DBP formation.

GENERAL PRACTICE AND RELATIVE RISK CONSIDERATIONS

In general, a membrane desalting process produces permeate water that is considered chemically unstable and low in mineral content, which can lead to corrosion and associated secondary impacts within the distribution system. During treatment, the mineral composition of the water is significantly changed and then partially reconstituted to achieve stable finished water that can be distributed in pipes. Whether or not the ultimate composition of the finished water has a positive or negative impact on the viability of distribution system components, distributed water quality, and health of long-term consumers of desalinated water supplies remains for the most part unknown. Water that contains little to no hardness may be considered unhealthy for potable use by certain consumers, and water that contains no dissolved oxygen may be offensive and taste flat. Consequently, post-treatment of membrane desalinated water is required prior to storage and distribution for municipal water purveyors, and must include disinfection.

When applying NF, RO and EDR technologies, it is important that care be taken to produce finished water that is compatible with the existing distribution system. Problems can arise if the finished water contains too little alkalinity, hardness, dissolved oxygen, or sulfur turbidity. Synthetic RO and NF membrane processes effectively remove DBP precursors, pathogens, organics, salts and other solutes from the source water; EDR effectively removes salts and other charged solutes from the water. However, important substances like bicarbonate alkalinity are also removed from the water when using RO, NF and EDR processes, and bicarbonate alkalinity is necessary to produce and distribute stabilized water throughout the distribution system. Consequently, the choice and manner in which post-treatment is practiced will impact distributed water quality.

As water is transported through a distribution system, physical, chemical and/or microbiological transformations may occur, resulting in degraded water quality. Aged water distribution systems typically have achieved some state of quasi-equilibrium and have as a result minimal problems. However, changes in water quality and conditions can affect the existing equilibrium of water distribution systems significantly, particularly if new water supplies or different water supplies are used to supplement water resources for the community. This is often the case when existing groundwater supplies are converted to a mixture of surface water and desalted source waters because interactions occur in the bulk phase and with surfaces in contact with the product water. When blending waters from multiple sources, it is helpful to use a multi-objective technique to evaluate the optimum blend for a particular distribution system requirement.

Relative Risk of a Water Quality Event(s) in a Distribution System Impacting a Water Purveyor's Compliance With Regulations When Blending Desalted Permeate Into an Aged Distribution System

A summary of the expected regulatory impacts on water purveyors, after blending or replacing a current water supply with desalted permeate is listed in Table 7.1. The probability of having issues concerning a water purveyor's compliance with the provisions of the Surface Water Treatment Rule (SWTR) are shown as very low in Table 7.1. If the water purveyor has produced historically safe water and desires to integrate advanced treatment into their system, then the resulting blended water will be of higher quality in terms of SWTR regulations.

Experience has shown that when a dramatic change in steady state conditions occurs in an aged and mature water distribution system, an impact to the water chemistry will occur within the distribution system. This often occurs when utilities introduce and/or blend permeate water sources into their existing water supply. It is not uncommon for the distribution system to experience fluctuations in pH and water chemistry due to high DO concentrations and low alkalinity (buffering capacity). This can result in destabilization of the mineral and biofilm coating known to exist inside the distribution piping system. Customers may experience increased copper and lead concentrations at the consumer tap, red, black or turbid water, and water having objectionable tastes and/or odors. The expected impact will place the consumer at greater relative risk to distribution system-related compliance items, namely the Total Coliform Rule (TCR), Lead and Copper Rule (LCR) and secondary standards for iron, turbidity, color, and odor as shown in Table 7.1. Additional problems which can occur include increased pitting corrosion and an accelerated rate

Table 7.1
Relative probability of blending permeate into a distribution system causing a WQ event(s) impacting a water purveyor's compliance with regulations

Regulation	Relative probability of WQ issue in a distribution system affecting a utility's compliance with regulations
Surface water treatment rule(s)	Very low
Consumer confidence reports	High
Phase I VOCs	Low
Phase II SOCs and IOCs	Low
Phase IIA fluoride	Low
Phase V SOCs and IOCs	Low
Radionuclides	Low
Lead and copper rule (LCR)	High
Total coliform rule (TCR)	High
Disinfectant by-products (D/DBPs)	Low
Secondary standards	High

of distribution system piping deterioration, build-up of excessive scale within distribution system piping, degradation of consumer plumbing, plugging of water meters, and degradation of elastomeric and rubber gaskets used in the water distribution system. Each of these situations, if they occur, would lead to an increased number of water quality complaints received by utilities and to increased O&M difficulties and expenses.

Historical monitoring data indicates utilities have routinely complied with standards established by the TCR. In view of anticipated destabilization of biofilms and corrosion products (e.g., tubercles), the potential for non-compliance warrants significant concern. Non-compliance stems from the release of pre-existing coliforms that can be entrained into the water column and conveyed to consumer taps. While the current utility disinfection methodology is capable of meeting regulated coliform standards, the same may not be true if materials in equilibrium at the solid-liquid interface are destabilized when non-stabilized permeate is introduced into an older distribution system.

Utilities should consider the effects of introducing permeate water into their water supply and its effects of DBP regulations. It is anticipated that bromide from the desalted permeate water would likely increase brominated forms of DBPs, specifically dibromochloromethane, bromodichloromethane, bromoform, and bromate, if utilities attempted to maintain free chlorine residual without some form of advanced treatment. In that case, a "high" risk of regulatory violation would be projected. Consequently, the low risk for D/DBP noncompliance presented in Table 7.1 is based on the assumption that water purveyors would maintain chloramine disinfection unless advanced treatment is provided.

There is a high probability associated with violation of secondary standards concerning iron, turbidity, color, odor, and corrosivity when introducing a new permeate water supply into a utility's distribution system. As stated, permeate water can destabilize mineral coatings known to exist on the inside of pipe walls, causing red, black or turbid water, and water having objectionable tastes and/or odors. As a result, it is anticipated that CCRs may be impacted because of additional contaminant monitoring under the revisions of the SDWA relative to the CCL. If any of the CCL

Table 7.2
Probability and degree of risk associated with a water quality–related post-treatment event

Parameter(s)	Event low probability (unlikely to occur)		Event high probability (likely to occur)		Recommended action
	Low health risk	High health risk	Low health risk	High health risk	
Lead and copper				✓	Distribution system issues and corrosion control treatment impact this parameter—should review and modify corrosion control/water treatment methods; then perform new lead and copper study.
Color*			✓		Modify treatment to maintain stability and reduce variation in pH, calcium and alkalinity.
Cryptosporidium and *Giardia*		✓			Prime responsibility for compliance; monitor impact in system if blending with other surface water—low risk.
DBPs	✓				Remain up to date and current on literature and consider monitoring for unregulated species (iodinated DBPs).
Turbidity†			✓		Modify corrosion control/water treatment methods to minimize.
Biostability			✓		Modify corrosion control/water treatment methods to minimize biofilm release and monitor impact in system. If a continued problem, advanced treatment techniques for AOC and BDOC removal may be required.
Taste and odor			✓		Water treatment and distribution system operation issue: (1) modify corrosion control/water treatment methods to minimize and (2) implement a rigorous distribution system monitoring and flushing program.

*Color as presented here refers to discolored red, brown or black water, pipe biofilm release, iron turbidity or sulfur turbidity.
†Turbidity is defined as non-microbial related.

chemicals being monitored in the system are detected above a detection limit, they must be added to the CCR for that specific community. These are chemicals for which no standard has yet been established. A greater potential exists for surface waters to contain some of these candidate compounds; however, the membrane process would have removed such contaminants.

Relative Risk of Post-Treatment Related Water Quality Event and Possible Impact

Table 7.2 summarizes both the probability of water quality parameter-related events occurring and the risk to public health of the event(s). As Table 7.2 indicates, although some parameter-related events have a low probability of occurring, they carry a high risk to public health if an event were to occur. Risks associated with parameter-related events apply primarily to public health. However, potential impacts upon the distribution system and water treatment facilities cannot be ignored, particularly if recurring events require pipe replacement in the distribution network and optimization or replacement/abandonment of water treatment facilities in favor of advanced drinking water treatment processes.

The probabilities and risks presented in Table 7.2 are predicated upon currently available data, interpretation of the data collected in this study and other studies, review of current literature, and historical information on RO, NF and EDR systems. The following parameter(s) are summarized for consideration when implementing plans to blend permeate into an aged water distribution system:

- Changes in lead and copper concentrations are highly probable due to corrosion effects discussed earlier. The risks to public health associated with such exceedances are considered high due to the adverse health impacts associated with these metals.
- *Cryptosporidium* and *Giardia* are water-borne protozoan parasites that have been found in some municipal water systems supplied by surface water or groundwater under the influence of surface water. The parasites are shed in the feces of infected humans and animals. The parasites cause fever, diarrhea, cramping, and anorexia. Immuno-compromised individuals are particularly at risk. No known therapies are currently developed for Cryptosporidiosis. These risks are low when membrane processes are employed for desalting. However, several of the participant utilities employing synthetic membrane processes for surficial saline supplies expressed concerns regarding *Cryptosporidium* present in these source waters despite the use of these advanced technologies. Because water purveyors desalt their supplies using advanced membrane technologies, the probability of a *Cryptosporidium* related event is unlikely to occur; however, several of the participant utilities expressed concern that such an event could have a significant impact on health. Consequently, for surficial brackish and seawater sources, water purveyors must assess their individual water supplies for risks associated with *Cryptosporidium* and *Giardia*.
- Disinfection byproducts (DBPs) are regulated by USEPA because of demonstrated carcinogenic activity in laboratory animals. Currently, only TTHMs and $THAA_5$ are the only regulated DBPs. If a utility converts from chloramines to free chlorine residual disinfection in a blended water, regulatory DBP compliance would be difficult. Bromide can permeate the membrane, and the formation of brominated THMs is favored when bromide ions are present. Consequently, the use of free chlorine disinfectant when bromide ions are present should be avoided. When chloramines are utilized, this effect is much less likely to occur, since the less reactive chloramines form fewer regulated THMs. However, when chloramines are used, iodated DBPs could be formed should iodide permeate the membrane (i.e., in a seawater desalting process) and are an emerging concern. Also, with respect to permeate, the participating utilities employing seawater sources noted that chloramine residual stability was an issue. The low probability, low health risk indicated in Table 7.2 is based upon the assumption of maintaining the chloramine residual provided in the projected source water blend unless advanced treatment is used with regards to THM. In addition, DBPs are considered a low health risk for this analysis because DBPs are considered chronic in nature and not considered as a single acute event. However, some questions remain, particularly with respect to emerging DBPs. Recent epidemiological studies have correlated dibromochloromethane with the occurrence of spontaneous abortion. If such effects are found to occur at low concentrations of brominated DBPs, public health and regulatory compliance issues may require attention. The technical literature should be continually monitored concerning DBP-related issues.

- *Biostability.* The potential for greater regrowth and impacts to the biostability of the existing and new biological growths within the distribution system will be highly probable due to the projected changes in water chemistry and the anticipated variability of the utilities source water. Sloughing of biofilms produces suspended solids, color, taste and odor at the consumer's tap. Also, the projected variable nature of the blended source water will make it difficult to establish continued biostability without a high probability of at least intermittently continuing biofilm sloughing. The public health risk of such sloughing is dependent upon the microorganism species present in the biofilm material, which is at present uncertain. Consequently, Table 7.2 indicates a high probability of occurrence with uncertainty as to health risk due to exposure. Since biofilm release is undesirable under any circumstance, modification of water treatment practices to minimize biofilm release would act to minimize exposure and health risk.

TYPICAL POST-TREATMENT UNIT OPERATIONS AND PROCESSES

Post-treatment consists of several different unit operations for RO and NF membrane systems. The steps chosen and their sequence depend on the designer's preferences and water quality goals. The primary post-treatment unit operations are aeration for hydrogen sulfide removal by and disinfection. Alkalinity recovery is also of concern in post-treatment, because it impacts the stability of finished water. The typical sequence of post-treatment unit operations used by utilities includes hydrogen sulfide removal followed caustic addition/alkalinity recovery and disinfection. It may be beneficial for utilities to slightly alter their sequence of post-treatment operations to include alkalinity recovery ahead of hydrogen sulfide removal followed by disinfection and then caustic addition. The purpose of this section is to demonstrate and compare the effects both sequences of unit operations on finished water quality through examples. The first set of design examples assumes the altered sequence of unit operations: alkalinity recovery, hydrogen sulfide removal and disinfection. The second set of examples demonstrates the typical post-treatment sequence of operations: hydrogen sulfide removal, caustic addition/alkalinity recovery and disinfection.

A systems view of post-treatment can help a designer to realize important goals. The membrane process removes essentially all pathogens and the majority of the DBP precursors, salts, and other solutes in the feed stream. Solute removal eliminates inorganic carbonate alkalinity, but all dissolved gases including carbon dioxide and hydrogen sulfide pass through the membrane (Lovins et al. 2004b). The designer must produce finished water after post-treatment with an appropriate alkalinity profile and disinfection without significant sulfur turbidity. An example of post-treatment water quality changes by unit operation are provided in Table 7.3. The changes in water quality are calculated using the following examples. The simulated permeate water quality is based on one of the participant utilities that relies on membranes for treatment of brackish groundwater. The water quality resulting from each post-treatment unit operation is illustrated in Table 7.3.

Table 7.3

Post-treatment water quality changes by unit operation

		Alkalinity recovery before aeration			Alkalinity recovery after aeration		
Water quality parameter	Permeate, mg/L	Tower inlet, mg/L	Tower outlet, mg/L	Stabilization and disinfection, mg/L	Tower inlet, mg/L	Tower outlet, mg/L	Stabilization and disinfection, mg/L
pH	4.79	6.00	7.8	7.8	4.79	7.8	7.8
H_2CO_3	113	80.0	1.25	1.25	113	0.113	0.113
HCO_3^-	2.92	35.1	35.1	35.1	2.92	3.0	3.0
Alkalinity, mg/L as $CaCO_3$	1.58	28.8	29.0	29.0	2.39	2.50	2.50
H_2S as S	2.00	2.00	0.181	0	2.00	0.0201	0
SO_4^{-2}	9.09	9.09	9.09	9.09	9.09	9.09	9.09
Cl^-	9.42	9.42	9.42	12.6	9.42	9.42	11.6
Ca^{+2}	2.45	14.0	14.0	14.0	2.45	2.45	2.45
Na^+	6.15	6.15	6.15	6.15	6.15	6.15	6.15
TDS	31.8	75.4	75.4	79	31.8	31.9	34.1
DO	0	0	8.24	8.24	0	8.24	8.24
Cl_2	0	0	0	2	0	0	2

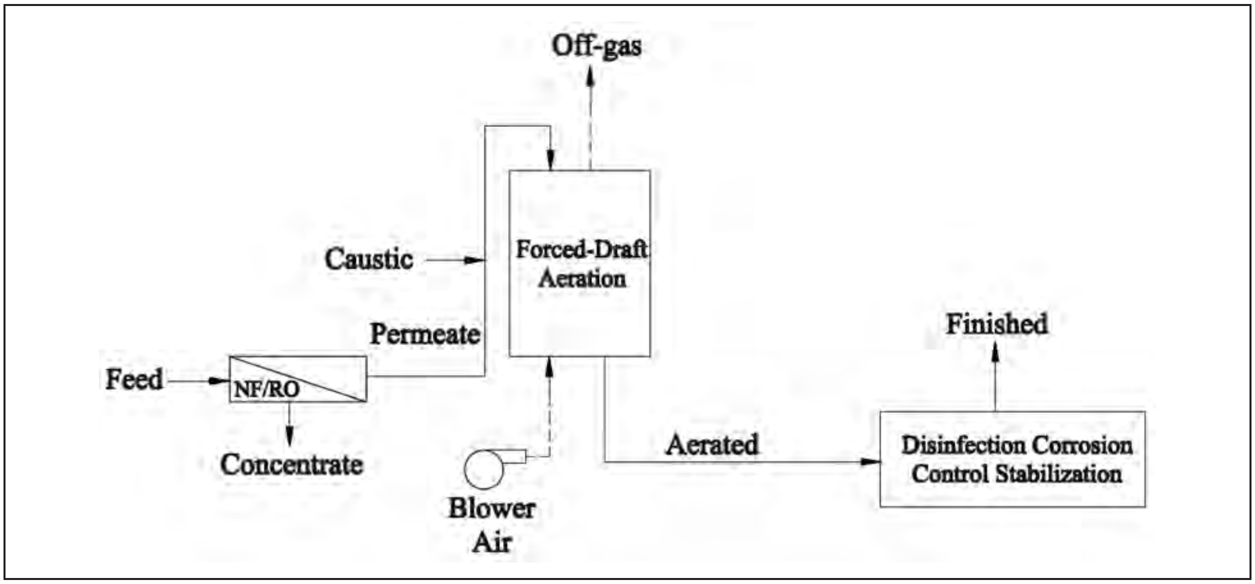


Figure 7.1 Alkalinity recovery process flow diagram

Alkalinity Recovery

Alkalinity recovery becomes a consideration during scaling control. The addition of acid to the feed stream prior to membrane treatment will prevent scaling, but because of the decrease in pH, alkalinity in the form of bicarbonate (HCO_3^-) will be converted to carbonic acid or gaseous carbon dioxide as shown in Equation 7.1. Carbon dioxide gas will pass through the membrane during treatment.

$$HCO_3^- + H^+ \leftrightarrow H_2CO_3 \leftrightarrow CO_2\,(g) + H_2O \qquad (7.1)$$

Membranes are a closed system and the carbon dioxide will remain under pressure until exposed to an open system. The presence of excess carbon dioxide presents the ability to recover alkalinity by caustic addition converting some carbon dioxide back to bicarbonate, which represents alkalinity. Exposure of the permeate stream to an open system occurs in the removal of hydrogen sulfide using aeration. Unless the pH is increased prior to aeration, the excess CO_2 will leave the system along with hydrogen sulfide and the potential to convert carbon dioxide to alkalinity will be lost. In an alkalinity recovery system, a fraction the excess dissolved CO_2 is converted to alkalinity in the form of HCO_3^- by adding caustic downstream of permeate prior to air stripping with packed towers. The conversion of aqueous carbon dioxide or carbonic acid to bicarbonate is shown in Equation 7.2.

$$H_2CO_3 + OH^- \rightarrow HCO_3^- + H_2O \qquad (7.2)$$

Figure 7.1 depicts an alkalinity recovery process flow diagram that further illustrates this concept. Normally, finished waters with 1 to 3 meq/L of bicarbonate alkalinity are considered highly desirable for corrosion control. Table 7.3 illustrates how pH increases, and alkalinity and hydrogen sulfide concentrations change following the unit operations discussed.

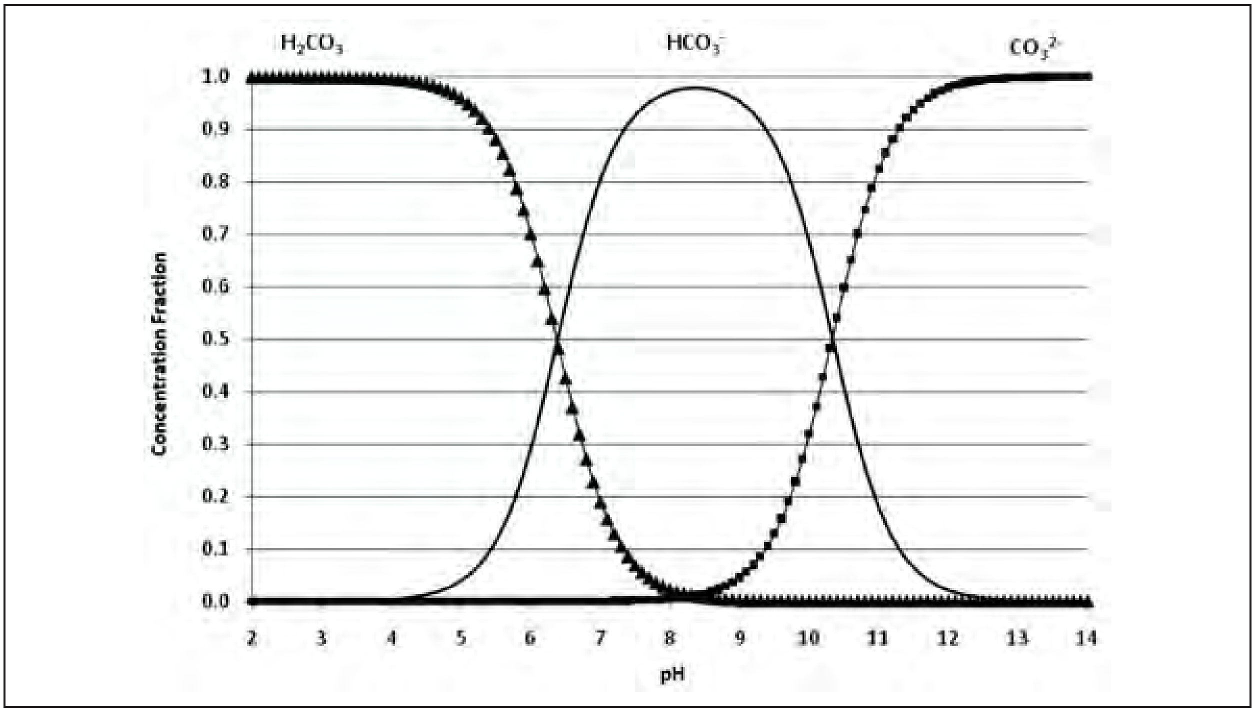


Figure 7.2 Carbonate system

Example 7.1 Alkalinity Recovery

Given: This example illustrates the alkalinity recovery process prior to aeration to remove hydrogen sulfide. The initial permeate water quality is shown in Table 7.3: pH = 4.79, H_2CO_3 = 113 mg/L, and HCO_3^- = 2.92 mg/L. In this example, a pH of 6 is desirable in order to recover some bicarbonate alkalinity while maintaining a pH below 7 prior to aeration. Calcium oxide, CaO, is used for the caustic addition.

Solution: The carbonate system is represented by H_2CO_3, HCO_3^- and CO_3^{2-}, and the total concentration of this system, C_T, is equal to the sum of the concentrations of each of the species. The permeate from the RO membrane process prior to aeration represents a closed system. In a closed system, the total concentration of the carbonate system does not change; however individual concentrations of carbonate species, H_2CO_3, HCO_3^- and CO_3^{2-}, can increase or decrease by changing the system pH. Figure 7.2 represents the fraction of each of the species in the carbonate system at varying pH values. At the permeate pH of 4.79, carbonic acid, H_2CO_3, is the dominant species, as seen in Figure 7.2. Adjusting the system pH to 6.0 would result in the conversion of some carbonic acid to bicarbonate, which will increase the alkalinity of the water. Further adjustment of the system pH would increase the alkalinity further; however, the system pH needs to be low enough to allow for efficient removal of hydrogen sulfide. This subsequent unit operation will be discussed in the next example. The following calculations demonstrate this theory.

The following equations are used for calculations and are derived from acid/base equilibrium chemistry of the carbonate system:

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3]} = K_{A1} = 10^{-6.35} = 4.3x10^{-7} \tag{7.3}$$

$$\frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} = K_{A2} = 10^{-10.33} = 4.7x10^{-11} \tag{7.4}$$

$$C_T = [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}] \tag{7.5}$$

$$[H^+][OH^-] = K_W = 10^{-14} \tag{7.6}$$

Solutions of these equations for the individual carbonate species gives:

$$[H_2CO_3] = \alpha_0 C_T = \frac{C_T}{1 + {K_{A1}}/{[H^+]} + {K_{A1}K_{A2}}/{[H^+]^2}} \tag{7.7}$$

$$[HCO_3^-] = \alpha_1 C_T = \frac{C_T}{1 + {[H^+]}/{K_{A1}} + {K_{A2}}/{[H^+]}} \tag{7.8}$$

$$[CO_3^{2-}] = \alpha_2 C_T = \frac{C_T}{1 + {[H^+]}/{K_{A2}} + {[H^+]^2}/{K_{A1}K_{A2}}} \tag{7.9}$$

Find the concentrations of carbonate species at initial system pH = 4.79. Initial carbonic acid and bicarbonate concentrations are known:

$$[H_2CO_3] = 113\frac{mg}{L} = 1.82 \times 10^{-3} = 10^{-2.74}$$

$$[HCO_3^-] = 2.92\frac{mg}{L} = 4.79 \times 10^{-5} = 10^{-4.32}\ M$$

Rearrange Equation 7.4 to solve for carbonate concentration:

$$[CO_3^{2-}] = \frac{(10^{-10.33})[HCO_3^-]}{[H^+]} = \frac{(10^{-10.33})(10^{-4.32})}{10^{-4.79}} = 10^{-9.86} = 1.38 \times 10^{-10}$$

Find the total concentration of the carbonate system, using Equation 7.5:

$$C_T = [10^{-2.74}] + [10^{-4.32}] + [1.38 \times 10^{-10}] = 10^{-2.73} = 0.00187\ M$$

Find the concentrations of the carbonate species at adjusted system pH = 6 using Equations 7.7, 7.8 and 7.9:

$$[H_2CO_3] = \frac{10^{-2.73}}{1 + {10^{-6.35}}/{[10^{-6}]} + {(10^{-6.35})(10^{-10.33})}/{[10^{-6}]^2}} = 1.29 \times 10^{-3}\ M$$

$$[HCO_3^-] = \frac{10^{-2.73}}{1 + {[10^{-6}]}/{10^{-6.35}} + {10^{-10.33}}/{[10^{-6}]}} = 10^{-3.24}\ M = 5.75 \times 10^{-4}\ M$$

Table 7.4

Summary of carbonate system concentrations at initial and adjusted system pH

pH	$[H_2CO_3]$	$[HCO_3^-]$	$[CO_3^{2-}]$	C_T
4.79	1.82×10^{-3}	4.79×10^{-3}	1.38×10^{-3}	1.82×10^{-3}
6.0	1.29×10^{-3}	5.75×10^{-3}	2.69×10^{-8}	1.82×10^{-3}

$$[CO_3^{2-}] = \frac{10^{-2.73}}{1 + {[10^{-6}]}\big/{10^{-10.33}} + {[10^{-6}]^2}\big/{(10^{-6.35})(10^{-10.33})}} = 10^{-7.57}\ M = 2.69 \times 10^{-8}\ M$$

Table 7.4 summarizes the calculations made thus far. In order to increase the pH of the system, caustic addition is necessary. Lime or Calcium oxide, CaO, is used. The total concentration of the carbonate system is not affected, rather the calcium oxide reacts with the carbonic acid, raising the pH of the system and shifting the carbonic acid to bicarbonate and carbonate.

$$CaO + 2H_2CO_3 \rightarrow Ca(HCO_3)_2 + H_2O \tag{7.10}$$

$$CaO + H_2CO_3 \rightarrow CaCO_3 + H_2O \tag{7.11}$$

Addition of lime does alter the electroneutrality equation. Equation 7.12 shows electroneutrality before lime addition and Equation 7.13 shows electroneutrality after lime addition.

$$[H^+] = [OH^-] + [HCO_3^-] + [CO_3^{2-}] \tag{7.12}$$

$$[H^+] + [Ca^{2+}] = [OH^-] + [HCO_3^-] + [CO_3^{2-}] \tag{7.13}$$

Use Equation 7.13 to calculate the calcium necessary to raise the pH to 6.0:

$$2[Ca^{2+}] = [OH^-] + [HCO_3^-] + 2[CO_3^{2-}] - [H^+]$$

$$2[Ca^{2+}] = \left[\frac{10^{-14}}{10^{-6}}\right] + 10^{-3.24} + [x10^{-7.57}] - [10^{-6}] = 5.75 \times 10^{-4} M$$

$$[Ca^{2+}] = 2.87 \times 10^{-4} M$$

Calcium ion concentration can be related to calcium oxide concentration as follows:

$$CaO \rightarrow Ca^{2+} + O^{2-} \tag{7.14}$$

Use Equation 7.14 to calculate the necessary calcium oxide dose:

$$\left(\frac{2.87 \times 10^{-4}\ mol\ Ca^{2+}}{L}\right)\left(\frac{1\ mol\ CaO}{1\ mol\ Ca^{2+}}\right)\left(\frac{56.1\ g\ CaO}{mol\ CaO}\right)\left(\frac{1000\ mg}{g}\right) = 16.1\frac{mg}{L}\ CaO$$

Compare alkalinity of system before and after calcium oxide addition, using Equation 7.15 and convert to mg/L as $CaCO_3$:

Table 7.5
Summary of CaO dose and alkalinity calculations

CaO dose (mg/L)	Initial alkalinity (mg/L as $CaCO_3$)	Final alkalinity (mg/L as $CaCO_3$)	Alkalinity recovered (mg/L as $CaCO_3$)
16.1	1.58	28.8	27.2

$$Alkalinity\left(\frac{eq}{L}\right)=[OH^-]+[HCO_3^-]+2[CO_3^{2-}]-[H^+] \tag{7.15}$$

Initial:

$$Alkalinity=\left[\frac{10^{-14}}{10^{-4.79}}\right]+[10^{-4.32}]+2[10^{-9.86}]-[10^{-4.79}]=3.17\times10^{-5}\frac{eq}{L}=0.0317\frac{meq}{L}$$

$$Alkalinity=\left(\frac{0.0479\ meq}{L}\right)\left(\frac{mmol\ CaCO_3}{2\ meq}\right)\left(\frac{100\ mg\ CaCO_3}{mmol\ \ CaCO_3}\right)=1.58\frac{mg}{L}\ as\ CaCO_3$$

Final:

$$Alkalinity=\left[\frac{10^{-14}}{10^{-6}}\right]+[0.000559]+2[2.80x10^{-8}]-[10^{-6}]=0.558\frac{meq}{L}$$

$$Alkalinity=\left(\frac{0.559\ meq}{L}\right)\left(\frac{mmol\ CaCO_3}{2\ meq}\right)\left(\frac{100\ mg\ CaCO_3}{mmol\ \ CaCO_3}\right)=27.9\frac{mg}{L}\ as\ CaCO_3$$

Table 7.5 summarizes the results of these calculations.

Discussion: Increasing the system pH decreased the carbonic acid concentration from 1.8 × 10^{-3} M to 1.29 × 10^{-3} M which is a difference of approximately 5.1 × 10^{-4} M, shown in Table 7.4. The carbonic acid was not lost, but rather shifted to equivalent concentrations of bicarbonate and carbonate. The bicarbonate concentration increased from 4.79 × 10^{-5} M to 5.75 × 10^{-4} M, which is a difference of approximately 5.3 × 10^{-4} M, shown in Table 7.4. The carbonate concentration increased slightly, however majority of lost carbonic acid concentration is converted to bicarbonate. The calcium oxide dose necessary to achieve the increase in pH was calculated to be 16.1 mg/L, shown in Table 7.5. The alkalinity recovery step prior to aeration increased the total alkalinity of the permeate water from 1.58 to 28.8 mg/L as $CaCO_3$, shown in Table 7.5. This example demonstrates limited alkalinity recovery because hydrogen sulfide is present in this water. Hydrogen sulfide stripping requires a packed tower (stripping tower) inlet pH of less than the pK_1 of hydrogen sulfide, which is 7.0. Hence, it is necessary for alkalinity recovery to be balanced with hydrogen sulfide removal requirements. If lower levels of hydrogen sulfide were present, a higher amount of alkalinity recovery would be affordable without sacrifice of sulfide removal effectiveness. If more hydrogen sulfide were present, as shown in the permeate water quality shown in Table 7.3, the pH entering the tower would have to be lower thus limiting the amount of alkalinity recovery that takes place. Site specific evaluations are recommended.

Hydrogen Sulfide Removal

Many of the groundwaters used for feed streams to RO or NF plants contain hydrogen sulfide. Acid addition in the feed stream is common to avoid calcium carbonate scaling in the permeate stream, and permeate pH is commonly between 4.5 and 6.0. While this measure prevents scaling, the acid addition converts dissolved sulfide to gaseous hydrogen sulfide. Neither the conventional pretreatment process (microfiltration, acid, or antiscalant addition) nor the membrane process will remove hydrogen sulfide. Aeration and oxidation are the two primary means of removing hydrogen sulfide; however, the involved chemical reactions are not well defined. An often neglected problem in the hydrogen sulfide removal processes is the formation of elemental sulfur. Elemental sulfur has been shown not to form during the chlorination of hydrogen sulfide if the reaction pH is less than 3.7; sulfate is the predominant reaction product at this pH. However, both entrained oxygen and chlorine will react with hydrogen sulfide to form elemental sulfur at pH levels above 4.0, as shown here.

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \tag{7.16}$$

$$2H_2S + O_2 + 2H_2O \rightarrow 2H_2SO_4 \tag{7.17}$$

$$H_2S + Cl_2 \rightarrow S + 2HCl \tag{7.18}$$

$$H_2S + 4Cl_2 + 4H_2O \rightarrow H_2SO_4 + 8HCl \tag{7.19}$$

The pK_{a1} for hydrogen sulfide is 7.0, and H_2S gas can essentially be removed at pHs below 6.37 without significant turbidity formation in an air-stripping or packed tower process. Aeration using tray aerators are less efficient at hydrogen sulfide removal, because there is less available surface area for air stripping. As such, residual sulfide remains in the water allowing elemental sulfur to form due to oxygen oxidation. While air-stripping or packed tower processes generally will avoid sulfur formation, available CO_2 important for the formation of inorganic carbonate alkalinity is also lost during the volatilization process. Consequently, unless a carbonate salt is added, pH is adjusted toward the bicarbonate species, or a significant amount of alkalinity passes through the membrane (which will not occur in brackish or seawater applications), there will be insufficient carbonate buffering in the finished water.

The final pH can be increased by the addition of sodium hydroxide downstream of the aeration processes, but the finished water will have very low buffering capacity and will be corrosive. Responses from many of the water purveyors that completed the questionnaire indicated that caustic addition downstream of the degassifier (packed tower or air stripper) was the method used for pH adjustment and stabilization for the permeate. A more useful application to consider would be to increase the pH close to the pK_1 of the bicarbonate, 6.37, prior to packed tower air stripping with calcium hydroxide or sodium hydroxide to recover between 1 to 2 meq/L of alkalinity with minimal elemental (colloidal) sulfur formation. Ultimately, most brackish groundwater membrane plants rely heavily on air stripping with packed towers for H_2S removal rather than using chlorination for H_2S destruction.

Mass transfer theory development for the air stripping process is not shown in detail in this document since it is well developed in published literature (Kavanaugh and Trussel 1980; Amy and Cooper 1986; Howe and Lawler 1989; Lamarch and Driste 1989; Roe 1935; Powell and Von Lossberg 1948; Flentje 1937; Treybal 1980; Onda, Sada and Murase 1959; Duranceau, Anderson and Teegarden 1999). Full-scale air stripping process design for volatile gases for most water treatment applications can be performed using a known or assumed overall liquid phase mass transfer coefficient (MTC) which is often seen in the literature as k_la. k_la is the product of the liquid phase mass transfer coefficient, K_1, and the specific interfacial area, a, which is the mass transfer interfacial area in the system volume. The k_la is also known as the volumetric mass transfer coefficient. The k_la is unique for each type and size of air stripping packing material and is sometimes available from packing manufacturers but is frequently determined by pilot studies or predicted using models such as the Onda correlations (Odna, Sada and Murase 1959). The k_la is used to calculate the height of a transfer unit (HTU) which when multiplied by the number of transfer units (NTU) provides the required height of mass transfer packing needed to achieve a desired removal efficiency. For dilute, volatile gas air stripping (where the contaminant's liquid and gas phase mole fractions along with the liquid and gas volumetric flow rates and Henry's constant are known), the NTUs can be calculated from:

$$NTU = \frac{R}{(R-1)} \ln\left[\frac{C_{in}}{C_{out}} * \left(1 - \frac{1}{R}\right) + \frac{1}{R}\right] \tag{7.20}$$

where R is the stripping factor calculated from:

$$R = H\left(\frac{Q_{gas}}{Q_{liquid}}\right) \tag{7.21}$$

where H is Henry's constant and Q_{gas} and Q_{liquid} are the gas and liquid molar flow rates.

Howe and Lawler (1989) found the overall liquid phase mass transfer coefficient, k_la, to be independent of pH for the H_2S species and not for total sulfide. The Howe and Lawler research showed that optimal packed tower air stripping design can be achieved using conventional design parameters without considering chemical kinetics. They note however that pH dramatically affects the total sulfide removal that can be obtained. It has been shown that the overall liquid mass transfer coefficient is independent of pH yet will impact mass transfer within the packed tower as a result of the removal of acid gases.

Packed tower air stripping of a non-dissociative gas from water is a first order reaction and exhibits non-linear behavior due to the reduction in driving force in the mass transfer zone as the gas is stripped. A second order is added to the reaction when the impact of pH on acid-base dissociation is included. Air stripping hydrogen sulfide from groundwater is influenced not only by the impact of pH on the sulfide species dissociation but also by the carbonate species dissociation since carbon dioxide is also stripped in the tower. The influence of pH on sulfide species dissociation is known to be relatively linear in the pH range of concern which is 6 to 8. The influence of pH on carbonate species dissociation is found to be relatively linear from pH 6 to 7 and becomes non-linear from 7 to 8. Using the rate expression derived in Howe and Lawler (1989), the rate of sulfide removal can be shown to be a reaction that is first order in driving force and first order in α. The nonlinear behavior of sulfide removal through a packed tower should be equally influenced by mass transfer driving force and pH change.

Figure 7.3 displays pH versus packing depth for two air loading rates at one water flow condition at a feed water pH of 6.0, and illustrates the increase in pH as water moves through the pilot tower. The graph depicts the rise in pH due to the stripping of carbon dioxide and hydrogen sulfide. The feed water pH started at 6.0 pH units entering the tower top and increased to 7.9 and 8.0 pH units exiting the tower, respectively. Figure 7.3 shows that the change in pH is greatest in

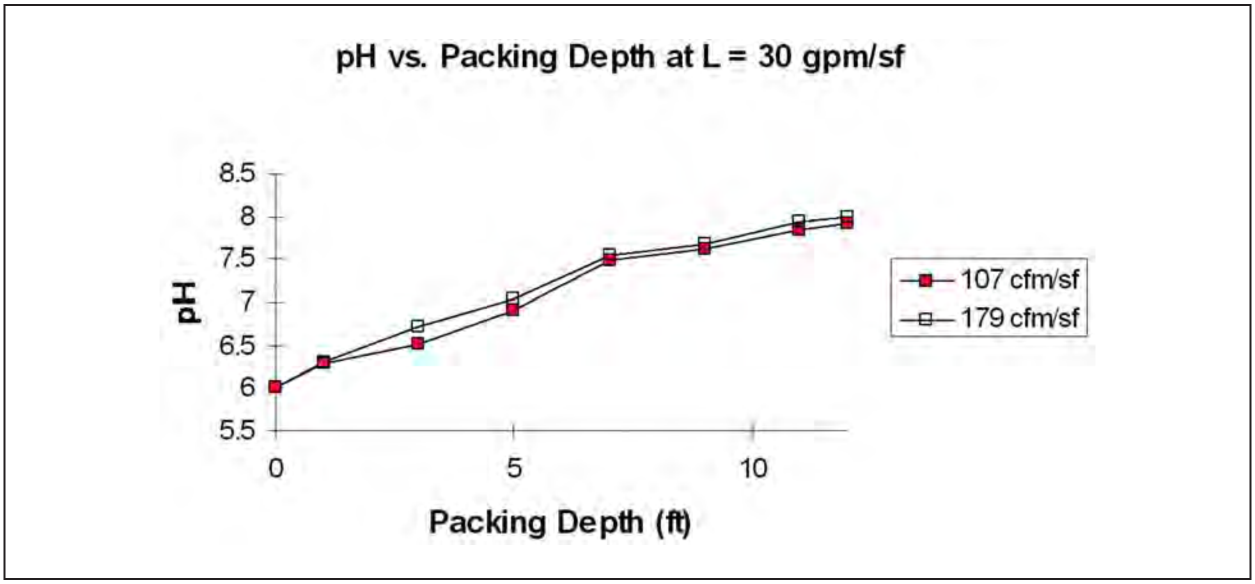


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Figure 7.3 Example of pH rise in a packed tower aeration process

the first foot of packing and gradually decreases until the pH reaches approximately 7. Near pH 7, there appears to be a slight increase in the rate of pH change. In the bottom half of packing at pH values above 7, the rate of pH change slowly decreases and becomes nearly linear. The rate of pH change follows closely with the rate of change in carbon dioxide gas ($H_2CO_{3,\ gas}$) available for stripping observed over the pH range 6 to 8.

Example 7.2 Hydrogen Sulfide Removal Using Packed Tower Aeration

Given: This example illustrates packed tower hydrogen sulfide removal given the permeate water quality following alkalinity recovery outlined in Example 7.1. In addition, this example illustrates how the remaining H_2CO_3 concentration from alkalinity adjustment will also be reduced. Following alkalinity recovery, the pH is equal to 6.0, shown in Table 7.3. Table 7.3 also shows that the permeate water contains a total sulfide concentration of 2 mg/L. The sulfide system is composed of three species, H_2S, HS^-, and S^{2-}, and the relative concentration of each species is dependent on the system pH. Figure 7.4 shows the sulfide system and the concentrations of sulfide species relative to system pH. Efficiency of removal of hydrogen sulfide gas, H_2S, is dependent on packed tower design and inlet system pH. Figure 7.4 shows that hydrogen sulfide is the dominant species at a pH less than 7, which is the pK_{a1} of hydrogen sulfide. Figure 7.4 shows that approximately 90% of the total sulfide concentration is in the form of H_2S at the system pH of 6.0. If the packed tower is designed correctly, approximately 90% of the total sulfide can be removed.

The permeate water enters a packed tower that receives a flow rate of 0.5 MGD and has a hydraulic retention time (HRT) of 10 minutes. Removal of total sulfide in the packed tower can be approximated using a first order relationship.

$$\frac{dC}{dt} = -kC \tag{7.22}$$

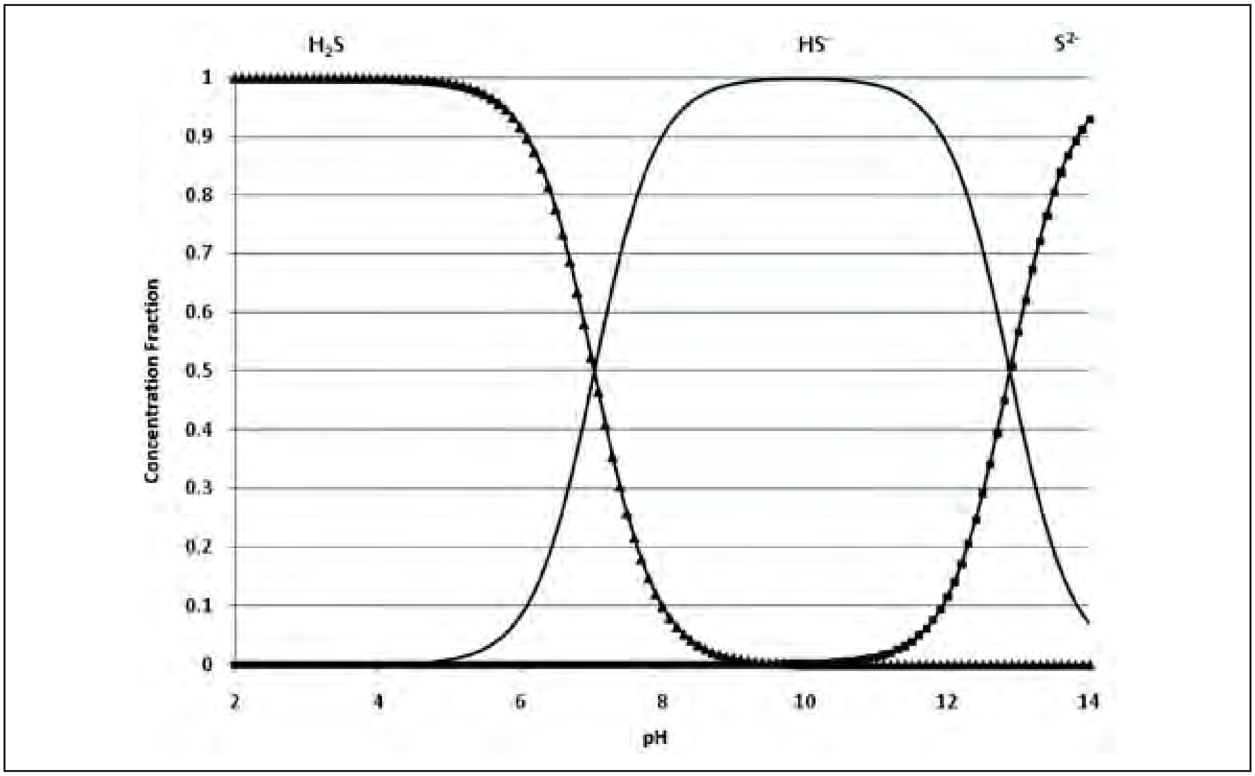


Figure 7.4 Sulfide system

It was determined that $k = 0.24\ \text{min}^{-1}$ for the packed tower. Following treatment within the packed tower, the remaining total sulfide is oxidized to the less odorous, and less corrosive, form of colloidal sulfur (sulfur with an oxidation number of zero). The oxidizing agent during this process is chlorine (Cl_2). Following complete conversion to colloidal sulfur, the original chlorine now exists as chloride (Cl^-). This example demonstrates how water quality changes after this series of processes.

Solution: Through the packed tower:

$$\frac{dC}{dt} = -kC \rightarrow \frac{dC}{C} = -kdt \rightarrow \int_{C_0}^{C_f} \frac{dC}{C} = -k \int_0^{HRT} dt \tag{7.23}$$

$$\ln\left(\frac{C_f}{C_0}\right) = -k(HRT) \rightarrow C_f = C_0 e^{-k(HRT)} \tag{7.24}$$

The remaining total sulfide concentration is calculated using Equation 7.24:

$$C_f = \left(2\frac{mg}{L}\right)e^{-(0.24\ \text{min}^{-1})(10\ \text{min})} = 0.181\ mg/L$$

Thus, packed tower aeration removed:

$$C_{removed} = \left(2\frac{mg}{L}\right) - \left(0.181\frac{mg}{L}\right) = 1.82\ mg/L$$

In addition, this same equation can be used to determine remaining H_2CO_3. Table 7.4 shows that the total concentration of the carbonate system is 1.87×10^{-3} M or 187 mg/L as $CaCO_3$. Figure 7.2 shows that about 70% of the carbonate system exists as carbonic acid or gaseous carbon dioxide at the system pH of 6.0. Therefore, approximately 70% of the total concentration of the carbonate system can be removed at this pH. The associated rate constant, *k*, for this process is 0.12 min^{-1}.

$$C_f = \left(187\frac{mg}{L}\ as\ CaCO_3\right)e^{-(0.12\ \text{min}^{-1})(10\ \text{min})} = 56.32\frac{mg}{L}as\ CaCO_3$$

$$C_{removed} = \left(187\frac{mg}{L}\ as\ CaCO_3\right) - \left(56.32\frac{mg}{L}\ as\ CaCO_3\right) = 130.7\frac{mg}{L}as\ CaCO_3$$

C_f represents the total concentration of the carbonate system following packed tower aeration, which is 56.3 mg/L as $CaCO_3$. Packed tower process removed 130.7 mg/L as $CaCO_3$ of the carbonate system. A decrease in the total concentration of the carbonate system is seen because the system changed from a closed to open system. Since the pH of the permeate water entering the tower was at 6, majority of the carbonate system was in the form of carbonic acid or gaseous carbon dioxide. The aeration process only removes gaseous compounds, thus it can be assumed that the decrease in the total concentration of the carbonate system was due to carbon dioxide gas leaving the system. The presence of the carbonic acid in the permeate water contributed to the low pH of the system since it is an acid. The removal of the acid results in an increase in pH. Figure 7.3 shows this trend. It is assumed that the pH of the permeate leaving the water is approximately 7.8. The system pH and remaining concentration of the carbonate system can be used to calculate the carbonic acid, bicarbonate, carbonate and alkalinity concentrations following aeration.

$$C_T = 56.32\frac{mg}{L}as\ CaCO_3 = 5.632 \times 10^{-4}M$$

$$[H_2CO_3] = \frac{10^{-3.249}}{1 + 10^{-6.35}\Big/[10^{-7.8}] + (10^{-6.35})(10^{-10.33})\Big/[10^{-7.8}]^2} = 2.01 \times 10^{-5}\ M$$

$$[HCO_3^-] = \frac{10^{-3.249}}{1 + [10^{-7.8}]\Big/10^{-6.35} + 10^{-10.33}\Big/[10^{-7.8}]} = 5.75 \times 10^{-4}M$$

$$[CO_3^{2-}] = \frac{10^{-3.249}}{1 + [10^{-7.8}]\Big/10^{-10.33} + [10^{-7.8}]^2\Big/(10^{-6.35})(10^{-10.33})} = 1.71 \times 10^{-6}M$$

$$[H_2CO_3] = 2.01 \times 10^{-5}\ M = 1.247\frac{mg}{L}$$

$$[HCO_3^-] = 5.75 \times 10^{-4}\ M = 35.1\frac{mg}{L}$$

$$[CO_3^{2-}] = 1.71 \times 10^{-6}M = 0.0572\frac{mg}{L}$$

$$Alkalinity\ = \left[\frac{10^{-14}}{10^{-7.8}}\right] + [5.75 \times 10^{-4}] + 2[1.71 \times 10^{-6}] - [10^{-7.8}] = 0.579\frac{meq}{L}$$

$$Alkalinity = \left(\frac{0.579\ meq}{L}\right)\left(\frac{mmol\ CaCO_3}{2\ meq}\right)\left(\frac{100\ mg\ CaCO_3}{mmol\ CaCO_3}\right) = 29.0\frac{mg}{L}\ as\ CaCO_3$$

$$[HCO_3^-] = 5.75 \times 10^{-4} M = 35.1\frac{mg}{L}$$

As shown, the final concentrations of bicarbonate and carbonate increase slightly following aeration due to the rise in the pH. This also slightly increased the alkalinity of the permeate water.

Stabilization pH and Disinfection

One way of determining the relative stability of permeate water during post-treatment operations is via calculation of the Langlier Saturation Index (LSI). The LSI is a corrosion index that is used to determine if a water is undersaturated, saturated or supersaturated with respect to calcium carbonate. The LSI is equal to the difference between the observed system pH, pH_{obs}, and the stabilization pH, often referred to as pH_s. Calculation of the pH_s is shown in Equation 7.25. The pH_s is important because of its historical use in the water industry and because it is desirable to have a slightly positive LSI in a drinking water distribution system. However, this cannot be achieved unless an understanding of the stabilization pH is established. The following examples should provide sufficient evidence to demonstrate that permeate of desalted brackish groundwater sources is unstable hence makes it difficult to easily achieve a positive LSI. This is because permeate is depleted of minerals, and as such is poorly buffered, which results in an elevated stabilization pH requirement. Comparison of the stabilization pH with the system pH allows purveyors to assess the stability of the permeate water following packer tower aeration and determine the type and order of subsequent treatment processes necessary to achieve a stabilized finished water. Disinfection with chlorine gas is also shown in this example.

$$pH_S = pK_2 - pK_{s0} + p[Ca^{2+}] + p[HCO_3^-] \qquad (7.25)$$

Example 7.3 Stabilization and Disinfection

The pH_s calculation following aeration is determined by equilibrium with $CaCO_3$ and can be calculated according Equation 7.25. Insight into the relative stability of this water can be achieved by comparing the pH_s with the system pH. This is demonstrated in the following calculation. The following equations, along with Equation 7.25 are referenced and used for calculation of the pH_s. In addition, the disinfection process is shown to remove any remaining total sulfide and establish a disinfection residual. The pH following disinfection is also calculated. Table 7.3 gives the permeate stream pH and concentrations of different species following packed tower aeration.

$$CaCO_3 = Ca^{2+} + CO_3^{2-} \qquad K_{sp} = 10^{-8.3} \qquad (7.26)$$

$$HCO_3^- = H^+ + CO_3^{-2} \qquad K_2 = 10^{-10.3} \qquad (7.27)$$

The concentrations of calcium and bicarbonate following packed tower aeration are shown in Table 7.3:

$$Ca^{2+} = 14.0\frac{mg}{L} = 3.48 \times 10^{-4}\ M$$

$$HCO_3^{-} = 35.1\frac{mg}{L} = 5.75 \times 10^{-4}\ M$$

Calculate p[Ca^{2+}]:

$$p[Ca^{2+}] = -\log[Ca^{2+}] = -\log[3.48 \times 10^{-4}] = 3.46$$

Calculate p[HCO_3^-]:

$$p[HCO_3^-] = -\log[HCO_3^-] = -\log[5.75 \times 10^{-4}] = 3.24$$

Using Equation 7.25 calculate the stabilization pH:

$$pH_S = pK_2 - pK_{s0} + p[Ca^{2+}] + p[HCO_3^-]$$

Equation 7.26 gives the pK_{sp} = 8.3. Equation 7.27 gives the pK_2 = 10.33.

p[Ca^{2+}] = 3.46

p[HCO_3^-] = 3.24

Insertion of these values into Equation 7.25 to obtain the stabilization pH:

$$pH_S = 10.33 - 8.3 + 3.46 + 3.24 = 8.73$$

The pH of the system is 7.8. A system pH less than the stabilization pH indicates that the water is still slightly aggressive towards calcium carbonate. Typically, it is desirable to have a system pH slightly greater than the stabilization pH as this indicates the water is slightly depositing of calcium carbonate. Further treatment processes following this could include addition of caustic or corrosion inhibitor in to achieve further stabilization of the permeate water. Typically the water purveyor that relies on membranes for desalting will produce finished water that is slightly less than the pH_s and hence by default rely on the distribution system for final stabilization.

During the chlorination process:

$$Cl_2 + 2e^- = 2Cl^-$$

$$S^{2-} = S^0 + 2e^-$$

$$Cl_2 + S^{2-} = S^0 + 2Cl^- \tag{7.28}$$

$$Cl_2 + H_2O \rightarrow HOCl + HCl \tag{7.29}$$

$$H_2S + 4HOCl \rightarrow SO_4^{2-} + 6H^+ + 4Cl^- \tag{7.30}$$

Chlorination is initially used to remove the remaining hydrogen sulfide (recall that the concentration of hydrogen sulfide is given as sulfur (S)):

$$[Cl_2]\ Required = \left(0.181\frac{mg\ S}{L}\right)\left(\frac{1\ mmol\ S}{32\ mg\ S}\right)\left(\frac{4\ mmol\ Cl_2}{1\ mmol\ S}\right)\left(\frac{71 mgCl_2}{mmol\ Cl_2}\right) = 1.61\frac{mg}{L}Cl_2$$

In this example calculation above, chlorine as Cl_2 is shown to react with sulfide; however, in practice most desalting facilities utilize bleach (sodium hypochlorite) for disinfection, which will result in the same total mass of sulfide remove. Alkalinity is destroyed from this addition of chlorine gas as Cl_2 because chlorine gas reacts with water to produce hydrochloric acid, depressing the system pH. This effect is negated by the addition of caustic prior to distribution. Caustic addition will further stabilize the water to a system pH approximately equal to the pH exiting the packed tower, which is 7.8. Additional chlorine is added to maintain a disinfection residual. A concentration of 2 mg/L Cl_2 is desired.

Examples 7.1, 7.2 and 7.3 demonstrated post-treatment unit operations that included alkalinity recovery prior to packed tower aeration, which is not typically practiced. The next set of examples show the typical sequence of post-treatment steps to achieve a stabilized finished water. These include packed tower aeration, stabilization, caustic addition and disinfection.

Example 7.4 Hydrogen Sulfide Removal Using Packed Tower Aeration Without Alkalinity Recovery

Given: This example illustrates the hydrogen sulfide removal process using packed towers given the permeate water quality following membrane treatment. In addition, this example illustrates how the remaining H_2CO_3 from alkalinity adjustment will also be reduced. Following membrane treatment, the pH is equal to 4.79, shown in Table 7.3. Table 7.3 also shows that the permeate water contains a total sulfide concentration of 2 mg/L. The sulfide system is composed of three species, H_2S, HS^-, and S^{2-}. Relative concentrations of species are dependent on the system pH. Figure 7.4 shows the sulfide system and the relative concentrations of sulfide species relative to system pH. Efficiency of removal of hydrogen sulfide gas, H_2S, is dependent on packed tower design and inlet system pH. Figure 7.4 shows the hydrogen sulfide is the dominant species at a pH less than 7, which is the pK_1 of hydrogen sulfide. The pH of the inlet water to the tower is equal to 4.79, and Figure 7.4 shows that approximately 99% of the total sulfide concentration is in the form of H_2S at this pH. If the packed tower is designed correctly, approximately 99% of the total sulfide can be removed.

The permeate water enters a packed tower that receives a flow rate of 0.5 MGD and has a hydraulic retention time of 10 minutes. Removal of total sulfide in the packed tower can be approximated using a first order relationship, shown in Equation 7.22. It was determined that $k = 0.46\ min^{-1}$ for the packed tower. Following treatment within the packed tower, the remaining total sulfide is oxidized to the less odorous, and less corrosive, form of colloidal sulfur (sulfur with an oxidation number of zero). The oxidizing agent during this process is chlorine (Cl_2). Following complete conversion to colloidal sulfur, the original chlorine now exists as chloride (Cl^-). This example demonstrates how water quality changes after this series of processes.

Solution: The remaining total sulfide concentration is calculated using Equation 7.24:

$$C_f = \left(2\frac{mg}{L}\right)e^{-(0.46\ \text{min}^{-1})(10\ \text{min})} = 0.0201\ mg/L$$

Thus, packed tower aeration removed:

$$C_{removed} = \left(2\frac{mg}{L}\right) - \left(0.0201\frac{mg}{L}\right) = 1.98\frac{mg}{L}$$

Table 7.4 shows that the total concentration of the carbonate system is 1.87 × 10^{-3} M or 187 mg/L as $CaCO_3$. Figure 7.2 shows that about 97% of the carbonate system exists as carbonic acid or gaseous carbon dioxide at the system pH of 4.79. Therefore, approximately 97% of the total concentration of the carbonate system can be removed at this pH. The associated rate constant, *k*, for this process is 0.36 min^{-1}.

$$C_f = \left(187\frac{mg}{L}\ as\ CaCO_3\right)e^{-(0.36\ \text{min}^{-1})(10\ \text{min})} = 5.110\frac{mg}{L} as\ CaCO_3$$

$$C_{removed} = \left(187\frac{mg}{L} as\ CaCO_3\right) - \left(5.11\frac{mg}{L} as\ CaCO_3\right) = 181.9\frac{mg}{L} as\ CaCO_3$$

C_f represents the total concentration of the carbonate system following packed tower aeration, which is 5.11 mg/L as $CaCO_3$. Packed tower process removed 181.9 mg/L as $CaCO_3$ of the carbonate system. A decrease in the total concentration of the carbonate system is seen because the system changed from a closed to open system. Since the pH of the permeate water entering the tower was at 4.79, majority of the carbonate system was in the form of carbonic acid or gaseous carbon dioxide. The aeration process only removes gaseous compounds, thus it can be assumed that the decrease in the total concentration of the carbonate system was due to carbon dioxide gas leaving the system. The presence of the carbonic acid in the permeate water contributed to the low pH of the system since it is an acid. The removal of the acid results in an increase in pH. Figure 7.3 shows this trend. It is assumed that the pH of the permeate leaving the water is approximately 7.8. The system pH and remaining concentration of the carbonate system can be used to calculate the carbonic acid, bicarbonate, carbonate and alkalinity concentrations following aeration.

$$C_T = 5.11\frac{mg}{L} as\ CaCO_3 = 5.11 \times 10^{-5} M$$

$$[H_2CO_3] = \frac{10^{-4.29}}{1 + {10^{-6.35}}/{[10^{-7.8}]} + {(10^{-6.35})(10^{-10.33})}/{[10^{-7.8}]^2}} = 1.8 \times 10^{-6}\ M$$

$$[HCO_3^-] = \frac{10^{-4.29}}{1 + {[10^{-7.8}]}/{10^{-6.35}} + {10^{-10.33}}/{[10^{-7.8}]}} = 4.91 \times 10^{-5} M$$

$$[CO_3^{2-}] = \frac{10^{-4.29}}{1 + {[10^{-7.8}]}/{10^{-10.33}} + {[10^{-7.8}]^2}/{(10^{-6.35})(10^{-10.33})}} = 1.55 \times 10^{-7} M$$

$$[H_2CO_3] = 1.8 \times 10^{-6}\ M = 0.113\frac{mg}{L}$$

$$[HCO_3^-] = 4.91 \times 10^{-5} M = 3.0\frac{mg}{L}$$

$$[CO_3^{2-}] = 1.55 \times 10^{-7} M = 9.32 \times 10^{-3} \frac{mg}{L}$$

$$Alkalinity = \left[\frac{10^{-14}}{10^{-7.8}}\right] + [4.91 \times 10^{-5}] + 2[1.55 \times 10^{-7}] - [10^{-7.8}] = 0.05 \frac{meq}{L}$$

$$Alkalinity = \left(\frac{0.579\ meq}{L}\right)\left(\frac{mmol\ CaCO_3}{2\ meq}\right)\left(\frac{100\ mg\ CaCO_3}{mmol\ CaCO_3}\right) = 2.50 \frac{mg}{L} as\ CaCO_3$$

As shown, the final concentrations of bicarbonate and carbonate increase slightly following aeration due to the rise in the pH. This also slightly increased the alkalinity of the permeate water. However, the alkalinity of this water is very low following packed tower aeration, which translates into very low buffering capacity. This permeate water is very susceptible to changes in pH and water quality, and will most likely be aggressive towards treatment system components. Chemical addition is necessary to replace the alkalinity that was lost during the aeration process.

Example 7.5 Stabilization and Disinfection

The pH_s calculation following aeration is determined by equilibrium with $CaCO_3$ and can be calculated according Equation 7.25. Insight into the relative stability of this water can be achieved by comparing the pH_s with the system pH. This is demonstrated in the following calculation. Equations 7.25, 7.26 and 7.27 are referenced and used for calculation of the pH_s. In addition, the disinfection process is shown to remove any remaining total sulfide and establish a disinfection residual. The pH following disinfection is also calculated. Table 7.3 gives the permeate stream pH and concentrations of different species following packed tower aeration.

Solution: The concentrations of calcium and bicarbonate following packed tower aeration are shown in Table 7.3:

$$Ca^{2+} = 2.45 \frac{mg}{L} = 6.11 \times 10^{-5} M$$

$$HCO_3^{-} = 3.0 \frac{mg}{L} = 4.91 \times 10^{-5} M$$

Calculate $p[Ca^{2+}]$:

$$p[Ca^{2+}] = -\log[Ca^{2+}] = -\log[6.11 \times 10^{-5}] = 4.21$$

Calculate $p[HCO_3^{-}]$:

$$p[HCO_3^{-}] = -\log[HCO_3^{-}] = -\log[4.91 \times 10^{-5}] = 4.31$$

Using Equation 7.25 calculate the stabilization pH:

$$pH_S = pK_2 - pK_{s0} + p[Ca^{2+}] + p[HCO_3^{-}]$$

Equation 7.26 gives the $pK_{sp} = 8.3$. Equation 7.27 gives the $pK_2 = 10.33$.

$p[Ca^{2+}] = 4.21$

$p[HCO_3^-] = 4.31$

Insertion of these values into Equation 7.25 to obtain the stabilization pH:

$$pH_S = 10.33 - 8.3 + 4.21 + 4.31 = 10.6$$

The stabilization pH is calculated to be 10.6; however, the actual pH exiting the packed-tower is 7.8 and very unstable. The high stabilization pH is due to the lack of bicarbonate concentration in the water, which translates into poor buffering capacity. The aeration process removed most of the carbonic acid whereby eliminating the potential to recover alkalinity. The pH of the system is 7.8. A system pH less than the stabilization pH indicates that the water is aggressive towards calcium carbonate, and would be responsible for corrosion of metal components and dissolution of concrete structures if left untreated. For this reason it is typically desirable to have a system pH slightly greater than the stabilization pH to achieve water that is slightly depositing of calcium carbonate. Therefore most brackish desalination plants stabilize with a combination of blending, caustic and/or corrosion inhibitor addition. Caustic addition in the form of NaOH will raise the system pH; however, this will not increase the bicarbonate alkalinity of the water, which is desirable in terms of buffering capacity. Corrosion inhibitor addition will also be necessary to prevent corrosion events in the distribution system. It is therefore understood that corrosion events may occur because of the water's low buffering capacity, which causes the water to be susceptible to changes in pH and water quality. Many of the participant utilities highlighted this specific problem as one if not the most challenging aspect of permeate post-treatment. Typically the water purveyor that relies on membranes for desalting will produce finished water that is slightly less than the pH_s and hence by default rely on the distribution system for final stabilization.

A difference between the system pH and pH_s, the LSI, for Example 7.3 was calculated as –0.9. Recall that this example set (Examples 7.1, 7.2 and 7.3) demonstrated a post-treatment process that included alkalinity recovery prior to packed tower aeration. Although the LSI value was calculated to be less than one (indicating the water is slightly aggressive towards calcium carbonate), its relative stability is more desirable, in terms of the LSI corrosion index, than the LSI calculated for this example set (Examples 7.4 and 7.5). The LSI calculated for this example set was –2.8. When comparing these values, the LSI calculated for the second example set indicates that the water is more aggressive towards calcium carbonate. Recall that Examples 7.4 and 7.5 demonstrated typical post-treatment practice, which does not include alkalinity recovery prior to packed tower aeration. Also, the water quality for the first example set had an alkalinity of 29.0 mg/L as $CaCO_3$ while the alkalinity calculated for the second example set was only 2.50 mg/L as $CaCO_3$. Alkalinity is another water quality parameter used in determining the stability of finished water. Based on these calculations, it can be seen that the sequence of post-treatment operations can have a significant impact on water quality and stability. Consequently, additional thought and study should be included in permeate post-treatment decision making and implementation beyond current methodologies.

During the chlorination process:

$$Cl_2 + 2e^- = 2Cl^- \tag{7.28}$$

$$S^{2-} = S^0 + 2e^-$$

$$Cl_2 + S^{2-} = S^0 + 2Cl^-$$

$$Cl_2 + H_2O \rightarrow HOCl + HCl \tag{7.29}$$

$$H_2S + 4HOCl \rightarrow SO_4^{2-} + 6H^+ + 4Cl^- \tag{7.30}$$

Chlorination is initially used to remove the remaining hydrogen sulfide (recall that the concentration of hydrogen sulfide is given as sulfur (S)):

$$[Cl_2]\ Required = \left(0.0201\frac{mg\ S}{L}\right)\left(\frac{1\ mmol\ S}{32\ mg\ S}\right)\left(\frac{4\ mmol\ Cl_2}{1\ mmol\ S}\right)\left(\frac{71 mgCl_2}{mmol\ Cl_2}\right) = 0.178\frac{mg}{L}Cl_2$$

In this example calculation above, chlorine as Cl_2 is shown to react with sulfide; however, in practice most desalting facilities utilize bleach (sodium hypochlorite) for disinfection, which will result in the same total mass of sulfide remove. Alkalinity is destroyed from this addition of chlorine gas as Cl_2 because chlorine gas reacts with water to produce hydrochloric acid, depressing the system pH. This effect is negated by the addition of caustic prior to distribution. Caustic addition will further stabilize the water to a system pH approximately equal to the pH exiting the packed tower, which is 7.8. Additional chlorine is added to maintain a disinfection residual. A concentration of 2 mg/L Cl_2 is desired.

PILOT PLANT EVALUATIONS SHOULD CONSIDER POST-TREATMENT

Pilot plant testing offers the best method for evaluating the feasibility of a membrane application for a specific water supply. Typically, piloting has been necessary because fouling cannot be quantitatively predicted from water quality measurements alone. Fouling indices do provide an estimate of the potential for fouling, but unlike pilot-scale testing, are not predictive of long-term performance. Unfortunately, most pilot plants conducted do not adequately provide for post-treatment evaluations, particularly studies related to blending, disinfection and corrosion control. In addition, pilot testing of membranes is now more often required by many state regulatory agencies prior to receiving regulatory approvals and applicable permits. There are many reasons for pilot plant testing, some of which include:

- Pilot testing is mandated by state or local primacy regulatory agencies.
- Collect baseline raw water quality profiles that can be used to establish a basis of design.
- Collect operating membrane process data for cost and performance evaluations.
- Confirm that the permeate water quality meets the contractual, regulatory, and site-specific needs of the owner and engineer.
- Provide hands-on training for plant operations personnel.
- Demonstrate operation protocols and procedures.
- Allows for continued long-term investigations on process operations.
- Allows for research and development.

However, this list does not provide for significant insight into the impact of post-treatment on distribution water quality. Two of the most critical needs to the design of a membrane desalting plant are delineating the quality of the feed water going into the system and predicting the desired quality of the water being produced by the system. The permeate quality is significant because this will be what to a large extent determines post-treatment requirements, which requires an assessment of existing infrastructure an other potentially impacted water supplies since desalination is used to augment existing native supplies. Additional considerations for design include pretreatment, process feed pumping requirements, process monitoring and flow control, backwash and cleaning cycles, chemical feed equipment, and residuals disposal. These components are necessary to provide an estimate of the cost and allow a cost benefit evaluation to be conducted. Different membranes can produce different permeate water qualities depending on the feed water quality. Because most applications are unique, a site specific understanding is necessary for the proper design of the membrane system and the post-treatment processes required.

The demonstrated benefits of performing bench-, pilot- and demonstration-scale testing of NF, RO and ED/EDR processes has continued over the years. Brackish groundwater RO and EDR plants have been successfully designed, effectively constructed and successfully operated over the years. Typically, approximately 2000 hours of run-time are required to operate a pilot and obtain quality performance data. However, additional time may be required to conduct distribution system evaluations. Piloting could be considered a method to reduce the risk of unknown issues related to operating a membrane process with a specific raw water, and does provide hands-on experience for plant operations personnel. Issues related to long-term fouling experienced in non-brackish ground and surface water remain with NF, RO and ED/EDR, and should be assessed with pilot testing. In these cases longer testing intervals should be considered to capture seasonal variations and allow for the development of long term fouling assessments, particularly if biological and organic fouling are predicted. Instrument verification and calibration of flowmeters, pressure and temperature transmitters, and on-line pH and conductivity meters, and similar, are required for NF, RO and EDR pilot facilities.

CHAPTER 8
SUMMARY, CONCLUSIONS, AND GUIDANCE RECOMMENDATIONS

SUMMARY

Desalination of sea or brackish water is an important, rapidly growing source of drinking water around the world. The mineral composition of the water is significantly changed and then partially reconstituted to achieve stable finished water that can be distributed in pipes. Whether or not the ultimate composition of the finished water has a positive or negative impact on the viability of distribution system components, distributed water quality, and health of long-term consumers of desalinated water supplies remains for the most part unknown.

With a growing number of potable water purveyors turning to desalination processes as a means for augmenting existing drinking water supplies, it is important to understand the behavior of desalted permeate within the distribution system and possible issues that may arise if proper post-treatment of permeate is not practiced. Desalination water is considered corrosive due to its inherently low mineral content and is not suitable for consumption without post-treatment.

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 and hence is available with regards to post-treatment requirements and secondary impacts. The behavior of desalinated water in the distribution system remains largely non-documented, and potential issues that may arise after introducing desalinated water into existing distribution systems include impacts on internal corrosion control, disinfectants and disinfection by-products, hydraulics, infrastructure maintenance, aesthetics, and customer acceptance.

The research project was conducted to reveal lessons learned, survey the industry practice, and develop concepts and guidelines for the post-treatment stabilization of membrane permeate. The work also to highlighted existing information gaps and identified associated research needs.

POST-TREATMENT

Post-Treatment Is Required

Pure water is considered a reactive chemical. Water that contains little to no hardness would be considered unhealthy for potable use and is often found to be aggressive towards distribution system components. In addition, drinking water that contains no dissolved oxygen may be offensive and taste flat. Consequently, post-treatment of membrane desalinated water is required prior to storage and distribution for municipal water purveyors, and must include disinfection.

Table 8.1 presents the typical categorization of permeate post-treatment depending on source water type. There are four primary issues concerning the post-treatment water. These relate to blending, remineralization, disinfection and the materials used for storage and transport of the water to the tap. Desalinated water is often blended with other sources that contribute minerals to the final blended water. Seawater as a source for blending is limited due to issues related to corrosivity and taste if the blending levels exceed about 1%. Blending of permeate water with seawater results in the addition of sodium, potassium, calcium, and magnesium to drinking-water but also

Table 8.1
Typical post-treatment processes based on supply type

Supply type	Process	Examples of applicable post-treatment processes
Seawater	RO	1. Recarbonation. 2. Lime addition. 3. Calcite bed filtration. 4. pH and/or alkalinity adjustment. 5. Addition of corrosion inhibitors. 6. Primary and secondary disinfection. 7. Blending with fresh water supplies.
Brackish water (surface)	RO, NF, EDR	1. pH and/or alkalinity adjustment. 2. Addition of corrosion inhibitors. 3. Primary and secondary disinfection. 4. Blending with fresh water supplies.
Brackish water (ground)	RO, NF, EDR	1. Decarbonation (degasification) 2. Hydrogen sulfide stripping. 3. pH and/or alkalinity adjustment. 4. Addition of corrosion inhibitors. 5. Primary and secondary disinfection. 6. Blending with fresh water supplies. 7. Bypass blending with raw water supply.
Fresh water (ground)	NF, EDR	1. Decarbonation 2. Hydrogen sulfide stripping. 3. pH and/or alkalinity adjustment. 4. Addition of corrosion inhibitors. 5. Primary and secondary disinfection. 6. Blending with fresh water supplies. 7. Bypass blending with raw water supply.

will contribute bromide and iodide which are DBP precursors. Consideration should be given to the natural minerals present and whether these will result in finished water having unacceptable water qualities in addition to unacceptable taste and odor.

Membranes do not remove small, uncharged molecular contaminants or dissolved gases such as carbon dioxide, hydrogen sulfide and methane. If hydrogen sulfide is present in a source groundwater, it must be removed, typically by packed tower or air stripping processes prior to disinfection and distribution to consumers. If gaseous sulfides are removed in the stripping process, then provisions are also made to remove (scrub) the off-gas sulfides from the air stripping tower to prevent odor and external corrosion issues on surrounding buildings and infrastructure. The stripping of carbon dioxide and hydrogen sulfide raises the pH and reduces the amount of base needed to perform stabilization. Permeate is typically low in calcium, magnesium, alkalinity and may have a low pH if acid was used for pretreatment ahead of the membrane process. Since the permeate is corrosive to downstream piping and appurtenances, alkalinity and pH adjustments are accomplished with bases such as sodium hydroxide, and inhibitors may also be employed for corrosion control purposes.

There is also an issue regarding potential anthropogenic pollutants from a range of sources which need to be considered on a local basis taking into account potential pollution sources and threats. This is the case whenever any external and potentially minimally treated water source is used for blending. Disinfection and filtration of the blending water will be necessary if there is any possibility of microbiological or other regulated parameter contamination, in which case similar considerations regarding the formation of by-products in the blending water apply. Generally the natural organic matter or TOC content in finished water is very low and the yield of by-products from final disinfection would be expected to be low as a consequence (McGuire Environmental 2004). However, blending with other source waters can prove to be problematic for desalted permeate, should bromide be present, or should the blend not provide enough buffering to the desalted permeate resulting in an unstable finished water.

Chemicals and Post-Treatment Issues

Post-treatment may be achieved by the addition of chemicals as described in the literature. If this is undertaken there are three primary concerns that need to be addressed:

1. The quality of the additives and the introduction of chemical contaminants produced during the manufacture, storage, distribution and transport. Unlike pre-treatment chemicals, there are no downstream processes that will remove undesirable contaminants.
2. Controlling dose rates so that required concentrations are provided. This can prove difficult when dealing with permeate that contains little to no buffering capacity downstream of a membrane process, as without buffering rapid pH changes can occur with minimal dose of acid or base chemical.
3. Preventing or minimizing unwanted chemical reactions following chemical addition. This issue is similar to blending. Localized changes can occur at dosing points leading to fouling problems on a micro-scale, particularly when by-pass or blending is considered.

Brackish and Seawater Post-Treatment Methods

Post-treatment of the permeate water from the desalination processes can include several unit operations, each dependent upon the source water type and desalination method. Considerations of post-treatment, based on literature findings, include:

- Stabilization by addition of caustic hydroxide alkalinity is the most widely used approach for brackish desalinated permeate in order to provide corrosion control for metallic pipelines and distribution systems, although this method is often accompanied by the addition of corrosion control inhibitors. Stabilization can also be achieved by carbonate alkalinity adjustment, remineralization by blending with source water(s) and the use of caustic soda-carbon dioxide or calcite bed contactors have been reported.
- The enhanced removal of specific compounds (i.e., boron, silica, NDMA, etc.) is site specific and source dependent.
- Sodium hypochlorite and chlorine gas are most widely used for disinfection of desalinated water. However, the use of chloramines instead of chlorine for residual disinfection is more advantageous when product water must be conveyed over long distances (over 100 km), or when stored for long periods of time (several days) due to the significantly lower decay rate of chloramines compared to free chlorine.

- Use of ozone as a disinfectant for desalinated water is limited as this practice has the potential of forming bromate as a disinfection by-product.
- Blending of desalinated water for remineralization is suitable with brackish water, but only feasible to up to about 1% with seawater. The raw water used for blending should be pretreated for chemical and microbial control prior to mixing with the desalinated water.

The primary desalination water plant post-treatment unit operations for potable water supplies reliant upon brackish groundwater are the following (AWWA 2007; Duranceau, 1993):

- Carbon dioxide removal (degasification or decarbonation);
- Hydrogen sulfide removal (stripping) and odor control treatment (scrubbing);
- Alkalinity recovery, pH adjustment, stabilization and corrosion control; and,
- Disinfection.

Alternative treatments reported for use in seawater desalination post-treatment applications include (Withers 2005):

- Addition of carbon dioxide and excess lime;
- Filtration of carbon dioxide dosed permeate through limestone bed contactors;
- Application of sodium carbonate and hydrated lime;
- Application of sodium bicarbonate and calcium sulfate;
- Application of sodium bicarbonate and calcium chloride;
- Blending with a native low-salinity water source or by-pass blending.

Remineralization can be categorized into a series of four treatment processes: (1) chemical addition without lime or limestone; (2) carbon dioxide addition followed by limestone bed contactors for dolomitic dissolution, (3) carbonic acid addition followed by lime dosing; (4) blending with water containing high mineral content.

CONCLUSIONS

Literature Review Findings

A review of relevant literature indicated that post-treatment is required for desalted permeate, and would include consideration of possible impacts from blending, remineralization, disinfection, storage and distribution. Stabilizing permeate water is accomplished by effectively controlling aspects of post-treatment. Most of the literature pointed to the use of various chemical treatments to achieve post-treatment goals. Literature indicates that there are several considerations that should be taken into account when deciding post-treatment strategies, including the quality of the chemicals added, controlling dosage rates, and minimizing unwanted chemical reactions within the distribution system. It was found that primary post-treatment unit operations includes degasification (decarbonation) for CO_2 removal, air stripping for H_2S removal, alkalinity and pH adjustment for stabilization, corrosion control, and disinfection. Post-treatment unit operation performance is dependent on the source water type and the desalination process. Stabilization of finished water can typically be accomplished through the addition of carbonate alkalinity, the use of corrosion inhibitors, remineralization through blending with source water, disinfection, and enhanced removal of specific compounds.

Due to low mineral content of desalted water, blending with source water allows for the addition of mineral such as sodium, calcium, potassium, and magnesium. When seawater is used for blending, the ability to by-pass source water and blend permeate for stability is limited to one percent, and hence is not typically practiced. In addition, it has been reported that blending could be problematic if bromides are present because of the possible formation of regulated and non-regulated DBPs, and possible impacts of bromide on chloramines disinfection.

Effective disinfection of desalted water is accomplished by the use of sodium hypochlorite, chlorine gas, chloramines, and ozone. It is important to note that disinfection-by-product formation of blended finished water supplies could be greater when blending native source waters containing TOC with seawater permeate due to higher concentration of bromide in the permeate. Recently iodinated DBPs have gained more attention as evidence suggests their presence in many water supplies across the US; however, the relative contribution of seawater permeate to iodinated DBP formation due to the passage of iodide across the membrane remains in question. Stabilization and disinfection are required components of post-treatment processes.

Questionnaire Findings

Based on the information obtained from the literature review, 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.

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 (sodium hydroxide) 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. Treated ground and surface water were reported to be used to accomplish blending for some facilities. Specific details on blending were provided by some facilities who reported blending with ion exchange treated source water, by-passed raw groundwater, and lime-softened or calcite filtered groundwater. 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.

Chloramines 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 mg/L within the distribution system. Facilities reporting the use of chloramines indicated that residual goals of 4 mg/L leaving the plant is desired and was between 1 mg/L and 2.5 mg/L within the distribution system.

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. Blending options included:

1. Blending permeate with raw by pass water
2. Blending using water from lime softening, RO and NF processes
3. Blending with brackish water or water produced by ion exchange.

Facilities that were reliant upon using by-pass reported bypass blending ratios between ten and thirty percent. The survey conducted in this project provided information about facility's 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 0.15 MGD to 70 MGD and an average blending flow rate ranging from 2 to10.5 MGD.

One comment that was consistently provided by the reporting utilities that had experienced distribution system related problems when using permeate as part or all of their water portfolio was that pilot testing of the membrane process in concert with the post-treatment would be useful in identifying possible issues and aid to limit adverse impacts. Pilot testing can help determine issues related to such items as stabilization, degasification, disinfection, corrosion control, and blending concerns. Most facilities did not incorporate pilot post-treatment testing, yet did acknowledge they performed pilot testing for the membrane process. 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.

Lessons Learned—Expert Workshop Proves Beneficial

A workshop was conducted that brought together experts in the field of desalination where they could describe their experiences with post-treatment stabilization, share lessons they have learned, and offer guidance to utilities experiencing problems with post-treatment. The experts identified fourteen priority guidance recommendations to deal with the many issues associated with post-treatment, as were presented in Table 4.2.

The expert workshop was a positive and well-executed activity where fourteen priority issues were identified. The highest ranked priority was related to how utilities should approach post-treatment stabilization with regards to help and available information. The main idea behind this highest priority is that stabilization of permeate water is a mandatory component of post-treatment for desalination facilities. Utilities should explore and define consistency goals by evaluating how much variation their systems can withstand without experiencing problems in the distribution system, since there is a range of variability that a distribution system can tolerate when integrating desalinated water into an existing water distribution system.

The second highest-ranked priority dealt with permeate conditioning and corrosion control. This topic is interrelated to the highest priority topic identified in the workshop. NF and RO permeate are considered corrosive to many types of materials of construction. Permeate produced by synthetic membrane processes can be "aggressive" water that if not stabilized may cause internal damage to many of the components that make up the water distribution system. The utility is required to understand the interrelated issues between treatment and the distribution system with respect to regulatory compliance, distribution integrity, and reliability, and the premise plumbing impacts specifically related to lead and copper release at consumer taps.

The third highest priority pertains to the challenges of disinfection by products formation during and following post-treatment operations. Considerations must be made with regard to the type of disinfection(s) used and there potential for DBP formation, whether it be chlorinated chloraminated, brominated, or iodated species. With regards to pretreatment, the use of pH buffers must be taken into account when it comes to their impact on post-treatment. DBP precursors in bypass water must be considered as a contributor to the total DBP concentration in the distribution system, while providing for inactivation of pathogens. Seasonal changes as well as mixing different water sources in the distribution systems should be identified.

Other priorities were related to defining water quality goals that are assessed based on source water type. Since blending is commonly used to improve stability of permeate water, caution was offered by the workshop participants based on their experiences because there can be secondary impacts of blending in the distribution system with regards to consumer confidence and water quality; hence, planning and testing should be taking into consideration when blending. Additional priorities were related to classification of the source of blending to achieve finished water quality goals. Consumer acceptance is imperative, so educating the public on the regulations related to desalinated water and post-treatment is necessary. Pretreatment can affect post-treatment decisions and careful selection on unit processes and chemical addition should be considered prior to use.

Questions Resolved by the Research

The objective of this study was to review membrane post-treatment case studies, conduct expert workshops to report practical experiences, denote lessons learned, identify research gaps, and suggest desalinated water post-treatment guidelines relative to water quality. The research was intended to supply answers to a number of questions asked by water purveyors considering, or actively engaged in, the use and application of desalination. The following answers to the questions considered in the research are offered in hopes of providing benefit to the drinking water community:

- Water quality—What water quality parameters need to be identified as potential issues specific to desalinated waters as compared to more traditional sources?

  To stabilize permeate water and prevent corrosion (metal release) of piping systems and domestic plumbing, post-treatment is necessary to return some calcium hardness and bicarbonate alkalinity to the water. In many situations, post-treatment also includes the removal of carbon dioxide to raise the pH, hydrogen sulfide removal when required, and the addition of fluoride which is removed during the desalting process. Corrosion control is a priority when either directly pumping desalted finished waters into the distribution system or when blending different water sources from membrane process. The constituents of concern when establishing a post-treatment process strategy include pH which will be dependent upon the buffering capacity and bicarbonate alkalinity, temperature, calcium, sulfate, chloride, dissolved oxygen, boron, total dissolved solids concentration (conductivity) and corrosion indices. These parameters are interrelated in the final treatment process selected for post-treatment, depending on application and source water.
- Corrosion indices—What types of indices are useful? Are new indices needed to provide better estimates of useful life of pipe materials?

  Several indices have been developed to indicate the stability or corrosivity of potable water. Although no single index is definitive, and some may at times be misleading, potable water corrosiveness or scaling potential can be evaluated and determined with a combination of indices. Each index provides information on the nature of the potable water; however, many of the indexes found in the water treatment and corrosion control literature are only approximations. The most common corrosion index in use is the Langelier Saturation Index (LSI). However, the buffer intensity (β), calcium carbonate precipitation potential (CCPP), Casil index, Larson ratio, and Ryzner index are also typically considered. There is need for the development of a "post-treatment" index that is specific to synthetic membrane processes that considers both corrosivity impacts and disinfection impacts in a combined format or procedure. Many of the participant utilities identified the need for developing this concept in a computer "tool" format. Additional discussion is provided in the research needs section of this report.

- Corrosion control—What are the most economical methods for providing corrosion control? What impacts are there associated with permeate pH adjustment on alkalinity recovery and disinfection by-product formation?

  Many of the plants surveyed indicated that two or more methods for corrosion control had been incorporated into their design in dealing with post-treatment: pH adjustment was the most common economical method to be employed for permeate post-treatment. Blending of permeate with mineral-rich source water, either using source by-pass streams or via the blending of permeate with conventionally-treated native (non-saline) source water is a second popular economical method for corrosion control, as indicated in the case studies presented in Chapter 6. Another method often cited for use in permeate corrosion control is the addition of chemical inhibitor.

  – Blending: What criteria should be used for determining blend ratios of different water supplies? Can blending be accomplished in the distribution system or will storage, detention and mixing be required?

    Blending can improve the stability of the permeate streams by increasing the alkalinity and calcium content to reduce the corrosiveness of the desalinated water. The water to be used for blending may be the sources water for the RO process or from another source, and is limited to brackish waters having moderate to low TDS and no significant DBP precursor content. And although blending of desalinated water for remineralization is suitable with brackish water, no more than 1 percent of seawater can be relied upon for blending. Use of bypass blending or reliance on multiple source waters for blending will reduce the overall stress on the membrane system as it reduces the amount of water that needs to be treated and thereby reduces the operation costs on the system. Blended waters from coastal and estuarine areas may be more susceptible to contamination with petroleum hydrocarbons or algal toxins, which could give rise to taste and odor problems. It is necessary to study the effects of different blends to prevent secondary impacts within the distribution system. Should multiple sources be used, the utility should consider the need to develop a unidirectional flushing program or distribution system rehabilitation (including replacement) prior to the incorporation of a desalting process into existing infrastructure. In addition, the water purveyor may also need to increase storage reservoir size to be able to control the blending location of multiple source waters. In most cases, the water purveyor should expect to see an increase in its operational and maintenance expenses. The raw water used for

  blending should be pretreated for chemical and microbial control prior to mixing with the desalinated water.
  - Inhibitors: What, if any, are the secondary impacts associated with the use of corrosion inhibitors in permeate streams?

    Inhibitors have found wide spread use as a method of corrosion control and are often cited for use in permeate corrosion control; however, there were reported concerns about the secondary impacts that could occur if inhibitors were used as a process chemical. The most prominent forms of inhibitors used are polyphosphates, zinc phosphates, and silicates. These inhibitors control corrosion by several mechanisms, including sequestering of corrosion by-products (such as lead and copper, scale inhibition, development of a coating film on the pipe walls and buffering the water at the desired pH). Operating data indicate that the choice of inhibitor depends upon pH, alkalinity, calcium and total hardness, chloride, sulfide, iron concentrations, 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.
- Post-treatment Unit Operations—Are there certain issues to be aware of when employing specific unit operations for post-treatment applications? What constraints are involved on different post-treatment unit operations with regards to operability, reliability, aesthetics and environmental secondary impacts? Is there significant bacterial regrowth during distribution especially in warm/hot climates?

  Post-treatment processes typically include stabilization, disinfection and corrosion control, and can include degasification and/or air stripping processes if carbon dioxide and hydrogen sulfide gases are present in the permeate water. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies. The choice and sequence of post-treatment operations are typically determined by regulatory requirements, the design of the system, finished water quality criteria and water chemistry. The need for post-treatment generally depends on a number of factors, which includes chemical and microbiological safety, palatability and customer acceptability, and secondary impacts on wastewater influent. Microbial growth would be lower in a water system distributed solely with desalted, stabilized permeate, as in the case of the participating utility, Consolidated Water as there are no nutrients nor appropriate sustainable food source. However, other systems that blend native water supplies with desalinated seawater supplies may contend with microbial issues that impact distributed water quality. Groundwater typically contains higher levels of gaseous hydrogen sulfide, and because the membrane will not remove the hydrogen sulfide, post-treatment for odor control is required where packed towers are in operation.
- Pipe Loop Testing—Is pipe loop testing needed, and if so, what general guidance has been generated for pipe loop testing (i.e., pipe materials, flow conditions, size of pipe)? Are there better measures of corrosion than the use of coupons?

  Although pilot studies are often conducted for membrane process design that includes operational considerations with respect to pretreatment and source viability (i.e., fouling concerns), these pilot studies often do not include adequate consideration of post-treatment processes focused on specific distribution system related issues that are unique to that system. There are on the other hand a number of examples of corrosion control pilot scale (pipe loop) studies that have been conducted over the years, in part or entirely, for compliance with the SDWA's LCR. Corrosion control evaluations are typicallynecessary to evaluate the impacts of treatment changes on corrosivity of internal pipe and distribution system components, and include the evaluation of secondary impacts of identified treatment strategies. Pipe loop tests can incorporate other features of post-treatment with the goal of simulating one or more processes. For purposes of post-treatment evaluations, pipeloop testing racks shouldbe designed to include metal coupons of known weight and materials. Additional techniques that could be used in conjuction with coupons are linear polarization probes, resistance probes and electrochemical noise measurement techniques to integrate concepts related to crevice and pitting corrosion, not simply generalized plumbosolvency methods (i.e., Coupons). A number of techniques can be used and will depend on the scope and depth of the study, but consideration of related topics should be included in the design; for example, disinfection and residual maintenance; DBP formation; lead and copper corrosion inhibitor or pH adjustment tests, and bacteriological regrowth (coliform) evaluations could be integrated into a pilot investigation.Post-treatment corrosivity and stability studies are beneficial in providing information on chemical treatment selection and dosage amounts for post-treatment operations. This has been demonstrated as described in Chapter 6, case studies. Each of the utilities that implemented studies developed beneficial information although each individual study conducted differed in scope Hence, it is important to recognize that multiple sources of corrosivity data is required to fully evaluate this interdisciplinary subject matter, and pipe loops aid in these efforts.

- Disinfection—Can disinfection of permeate water impact other water supplies when introduced into a common distribution system? How does bromide concentration in the permeate impact disinfection by product formation potential if blended into a common water distribution system? Does bromide have an impact on residual stability?

  Disinfection is a required component of post-treatment, and the work presented herein indicated that chlorine and chloramines are the more common disinfection processes use to disinfect permeate streams. The EPA maximum residual disinfectant level (MRDL) of 4.0 mg/L disinfectant residual limits public exposure to chlorine in drinking water systems on a running annual average. Water systems practicing intentional chloramination will dose less than 1 mg/L of ammonia-N chemical to remain below the MRDL residual and avoid excess free ammonia. Without the proper ratio between chlorine dosage rate and ammonia addition (5:1 part Cl_2:NH_3-N) the formation of unstable combined residual will occur. Yet the choice of monochloramine in seawater permeate may not be an effective strategy due to the effect of permeate bromide content on monochloramine residual. Participant utilities expressed concerns with regards to disinfectant stability in seawater permeate and DBP formation in permeate blends of bypass or blend supplies. It has been documented that bromidecan impact residual stability and serve as a source for brominated DBPs. Because blending is a common option for cost effective permeate stabilization, evaluation of the blend or bypass streams with regards to water quality and DBP formation potential is also required. Those systems that practiced chloraminaton as with other systems reliant upon monochloramine residual for secondary disinfection residual requirements rely on distribution flushing as the primary strategy for controlling nitrification. Benefits of flushing are residual restoration, removal of microorganisms and DBPs, at the expense of labor costs, water loss and ammonia formation due to autocatalytic decay of the monochloramine residual itself.

- Taste Testing and Consumer Confidence–Public Acceptability—What problems, if any, may arise with regards to the public's acceptability? Should taste tests be conducted when establishing criteria for post-treatment?

  Most of the surveyed water utilities identified taste and odor as a major worry with respect to customer acceptance and consumer confidence. Although regulated as Secondary Contaminants per the SDWA, taste and odor of permeate is for the most part subjective. Taste refers only to sensations typically referred to as bitter, salty, sour and sweet, and is dependant upon the chemical substances present. Odor, like taste, depends on the chemical substances present in the water being consumed. Certain inorganic salts can produce tastes without odor, and as a result, permeate of desalinated water systems can appear to have a flat taste. If disinfectant is present, a perceived odor can also be noted. Customers have been known to register complaints to their water purveyor when a drastic change in water quality occurs, but given time will become accustomed to a new water quality, assuming no substantial changes to the variability of that quality. Stabilization will reduce the perceived reactions to desalted permeate, in addition to providing its primary associated benefit related to addressing internal corrosion control concerns. Taste tests could be conducted to establish some level of subjective criteria for post-treatment; however, corrosion control test rack studies are recommended as more effective study methods. Prior studies had indicated that the consumer prefers a blended water supply as desalted seawater permeate for drinking water; that is, the water needs to be stabilized else the consumer will object in some manner.

RECOMMENDATIONS

Based on the results of this study, stabilization and effective disinfection of permeate water is the most import aspect of post-treatment design and operation. It is recommended that water purveyors carefully assess the integration of desalination into their water portfolio, and in doing so, develop practical and reasonable post-treatment goals in addition to the goals typically developed for the desalination process itself.

Water Quality Goals for Post-Treatment Processes

The discussions provided herein this literature review indicate clearly that stabilization and disinfection are fundamentally important in the proper design and operation of post-treatment processes. It is therefore important to develop treatment goals and condition that can be used as a guide for developing post-treatment concepts. Although the development of these goals is site specific to the desalination source water and membrane process utilized in treatment, based on the results of this study including literature, survey and case study reviews, it is recommended that the goals presented in Table 8.2 be considered for desalination post-treatment processes (AWWA

Table 8.2
Desalination post-treatment water goals for POE

Parameter	Seawater	Brackish water
pH	6.5–9.5	7.5–8.4
Alkalinity (mg/L as $CaCO_3$)	50–125	75–150
Hardness (mg/L as $CaCO_3$)	50–85	75–110
Calcium concentration (mg/L)	50–75	60–100
TDS (mg/L)	100–500	85–350
Sulfate to chloride ratio	1–1.3	0.5–1
Turbidity (NTU)	0.6–3	0.2–2
Boron	0.5–1	NA

2007; Lahav and Birnhack 2007; Duranceau 2001; Appelgate 1986; Hasson and Bendihem 2006; Withers 2005; Delion, Mauguin and Corsin 2004; Shi and Taylor 2005; Taylor et al. 2005; Marangou and Savvides 2001; Yermiyahu et al. 2007).

It should be noted that the TDS content should be similar to other supplies when consecutive distribution systems are impacted by the inclusion of a desalination process into a water community's treatment portfolio. The goals in Table 8.2 are presented for use by municipal and/or other water purveyor entities whose primary function is to produce drinking water for consumption while meeting fire demand. Consideration of a stabilized and disinfected permeate (and its blends) SAR value should be taken into account when other water quality criteria are needed due to irrigation or vegetation concerns. An example of this is the consideration of permeate boron when seawater supplies are to be used in a system that includes irrigation as an end-use.

Recommended Post-Treatment Process Piloting Necessary for Design

The need to stabilize water so that it would not enhance metal corrosion and concrete dissociation has been recognized for decades. Permeate typically is adjusted chemically in order to prevent corrosion of pipes in the distribution network, pH value and carbon dioxide content for scaling prevention. As an example, a buffer intensity greater than 0.5 milliequivalents per pH unit is indicative of a balanced, stabilized source water; to accomplish this the finished water must have adequate alkalinity that may fall within a range of values that are largely dependent on source water treatment and blend water operations. Alkalinity recovery needs to be considered when selecting scaling control options, and depends on how much carbon dioxide and bicarbonate is in the raw water. Regardless, permeate water will require chemical disinfection. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies (Lovins et al. 2004b; Duranceau and Lovins 2005). Although pilot studies are often conducted for RO and NF process design considerations related to pretreatment and process optimization and operation considerations, these pilot studies do not include adequate consideration of post-treatment processes focused on specific distribution system related issues that are specific to the system incorporating the membrane process. It is recommended that water purveyors mandate studies to evaluate the secondary impact of permeate post-treatment (or lack thereof) on water quality and subsequent compliance related topics: disinfection and residual maintenance, the formation of disinfection by-products, maintenance of lead and copper corrosion control, bacteriological regrowth and coliform impacts.

Consequently, pilot plant testing that takes into account post-treatment processes is important to develop proper design to achieve overall drinking water goals for the distribution system. Most water purveyors understand the need to focus on pilot testing for the membrane process, however, as a result of this study that included an expert workshop, pilot testing should extend to include post-treatment processes that are to be implemented for the specific need. This could include such unit operations as degasification, air stripping, pH adjustment or chemical conditioning with bases or inhibitors, and must at a minimum require disinfection evaluations. Considerations for effective post-treatment should also include and understanding of feed water sources, address the potential of by-pass or native water blending for stabilizing permeate, the effect of alternative disinfectants when used (such as chloramines), and a realization to include programs to enhance and evaluate consumer confidence in these efforts.

Research Needs Identified in Second Expert Workshop

Another central phase of this research project was to conduct a workshop involving the participating utilities to identify research needs to address utilities' issues with post-treatment, and in doing so identify research 'gaps' in order to develop a listing of research needs. The workshop was a two-day event, held in southern California, beginning February 9 and ending February 10, 2009. The first day of the workshop was held at the Irvine Ranch Water District's (IRWD's) headquarters in Irvine, California. Representatives from the participating utilities began research needs workshop by answering the question, "In your opinion, what are the three most important post-treatment research needs today?" This discussion led to the development of nine key topics identifying the specific research needs for post-treatment. Table 8.3 presents the results of this effort.

Table 8.3
Identification of research needs

Research need	Issue	Possible outcome(s)	Impacts if not addressed
Chloramine residual stability in permeate water	• Bromides and iodides degrade chloramine disinfectant	• Better analytical methods for iodide and bromide • Improved technologies for removal of bromide and iodide • Increase understanding of bromide and iodide chemistry	• Reduced or eliminate disinfectant residual • Reduces ability to augment existing water sources that use chloramine disinfection
Formation of brominated and iodinated disinfection by products in desalted permeate and its blends	• Potential formation of brominated and iodated DBPs and their unknown health risks • Taste and odor caused by iodated DBPs	• Study effects of blending permeate with traditional water sources • Identifying conditions under which formation occurs specific to blended water	• Future non-compliance with possible regulations made to control current unregulated DBPs • Impacts on public health
Testing protocol for post-treatment of desalinated waters	• The need for testing protocols addressing possible post-treatment operations as permeate water quality is unique to each utility	• Gather information from major desalination plants specifically on water quality before and after introduction of new water sources • Compile existing case studies	• Decreased water quality • Damage to existing infrastructure • Decreased customer confidence • Higher replacement costs • Higher maintenance costs
Evaluation of the impact of seawater permeate post-treatment on existing infrastructure	• Distribution systems are different in materials used for construction and agel the introduction of new, blened water sources may have negative impacts on infrastructure due to water quality changing	• Evaluate changes in corrosivity of blended water sources • Develop guidelines for newer alternative materials of construction that are more compatible with blended water sources • Removal of incompatible materials	• Damage to infrastructure • Decreased water quality • Decreased customer confidence • High maintenance costs
Performance of corrosion-inhibitors or other stabilization chemicals	• Questions remain regarding effectiveness and performance of corrosion inhibitors	• Evaluation of current testing procedures for effectiveness of inhibitors • Develop predictive tool to assess manufacturer's claims regarding effectiveness of their product • Development of coating films for internal pipe surfaces	• Unforeseen damage to distribution system
Studying the effects of blending desalinated seawater permeates with ground and surface water sources on aesthetics and customer satisfaction	• Permeate water is aesthetically undesirable to consumers, however, permeate water is necessary to augment existing water sources, thus proper blending ratios of different waters as yet to be determined	• Pilot or bench scale studies that research various blending ratios • Identify specific constituents that affect taste and odor in blended supplies • Conducting public surveys to evaluate customer acceptance	• Decreased customer confidence

(continued)

Table 8.3 (Continued)

Research need	Issue	Possible outcome(s)	Impacts if not addressed
Software tool development for risk analysis in permeate blending with traditional ground and surface water sources	• Seasonal and site specific variations in water quality occur for permeate water and blended water, as such, a software tool is necessary that can adjust for these differences and assess the impact to the water community	• Site visits to appropriate utilities to gather information on infrastructure, materials, and treatment processes • Gather information on unique water quality • Develop a model that combines and relates all factors	• Adverse impacts on water quality • Unforeseen changes in permeate water and blended water • Decreased customer confidence
Identifying specific constituents in and possible reactions present from the blending of permeates from groundwater sources and permeates from SWRO permeates	• Little is known on possible reactions that may occur from blending different permeate sources	• Water quality assessment specific to permeate water • Bench of pilot scale studies specific to permeate water blends that test various blening scenarios	• Possible decreased water quality • Distribution system damage • Customer dissatisfaction
Identification of alternative post-treatment methods for removal of hydrogen sulfide	• Conventional treatment, nor membrane treatment will remove hydrogen sulfide from water • Existing removal technologies are costly, and labor and maintenance intensive	• Gather all information on existing technologies, especially those other than scrubbers • Possibly adjust or combine existing treatment methods to develop removal technology compatible with desalination treatment	• Hydrogen sulfide is can be corrosive and lead to distribution system damage • Taste and odor issues
Chloramine residual stability in permeate water	• Bromides and iodides degrade chloramine disinfectant	• Better analytical methods for iodide and bromide • Improved technologies for removal of bromide and iodide • Increase understanding of bromide and iodide chemistry	• Reduced or eliminate disinfectant residual • Reduces ability to augment existing water sources that use chloramine disinfection
Formation of brominated and iodinated disinfection by products in desalted permeate and its blends	• Potential formation of brominated and iodated DBPs and their unknown health risks • Taste and odor caused by iodated DBPs	• Study effects of blending permeate with traditional water sources • Identifying conditions under which formation occurs specific to blended water	• Future non-compliance with possible regulations made to control current unregulated DBPs • Impacts on public health
Testing protocol for post-treatment of desalinated waters	• The need for testing protocols addressing possible post-treatment operations as permeate water quality is unique to each utility	• Gather information from major desalination plants specifically on water quality before and after introduction of new water sources • Compile existing case studies	• Decreased water quality • Damage to existing infrastructure • Decreased customer confidence • Higher replacement costs • Higher maintenance costs

(continued)

Table 8.3 (Continued)

Research need	Issue	Possible outcome(s)	Impacts if not addressed
Evaluation of the impact of seawater permeate post-treatment on existing infrastructure	• Distribution systems are different in materials used for construction and agel the introduction of new, blened water sources may have negative impacts on infrastructure due to water quality changing	• Evaluate changes in corrosivity of blended water sources • Develop guidelines for newer alternative materials of construction that are more compatible with blended water sources • Removal of incompatible materials	• Damage to infrastructure • Decreased water quality • Decreased customer confidence • High maintenance costs
Performance of corrosion-inhibitors or other stabilization chemicals	• Questions remain regarding effectiveness and performance of corrosion inhibitors	• Evaluation of current testing procedures for effectiveness of inhibitors • Develop predictive tool to assess manufacturer's claims regarding effectiveness of their product • Development of coating films for internal pipe surfaces	• Unforeseen damage to distribution system
Studying the effects of blending desalinated seawater permeates with ground and surface water sources on aesthetics and customer satisfaction	• Permeate water is aesthetically undesirable to consumers, however, permeate water is necessary to augment existing water sources, thus proper blending ratios of different waters as yet to be determined	• Pilot or bench scale studies that research various blending ratios • Identify specific constituents that affect taste and odor in blended supplies • Conducting public surveys to evaluate customer acceptance	• Decreased customer confidence
Software tool development for risk analysis in permeate blending with traditional ground and surface water sources	• Seasonal and site specific variations in water quality occur for permeate water and blended water, as such, a software tool is necessary that can adjust for these differences and assess the impact to the water community	• Site visits to appropriate utilities to gather information on infrastructure, materials, and treatment processes • Gather information on unique water quality • Develop a model that combines and relates all factors	• Adverse impacts on water quality • Unforeseen changes in permeate water and blended water • Decreased customer confidence
Identifying specific constituents in and possible reactions present from the blending of permeates from groundwater sources and permeates from SWRO permeates	• Little is known on possible reactions that may occur from blending different permeate sources	• Water quality assessment specific to permeate water • Bench of pilot scale studies specific to permeate water blends that test various blening scenarios	• Possible decreased water quality • Distribution system damage • Customer dissatisfaction
Identification of alternative post-treatment methods for removal of hydrogen sulfide	• Conventional treatment, nor membrane treatment will remove hydrogen sulfide from water • Existing removal technologies are costly, and labor and maintenance intensive	• Gather all information on existing technologies, especially those other than scrubbers • Possibly adjust or combine existing treatment methods to develop removal technology compatible with desalination treatment	• Hydrogen sulfide is can be corrosive and lead to distribution system damage • Taste and odor issues

APPENDIX A
APPLICABLE LITERATURE

OSMOSIS AND PERMEATE MATHEMATICS

Background

In general, the permeate from membrane desalting process produces permeate water that is considered chemically unstable and low in mineral content, which can lead to corrosion within the distribution system. The mineral composition of the water is significantly changed and then partially reconstituted to achieve stable finished water that can be distributed in pipes. Whether or not the ultimate composition of the finished water has a positive or negative impact on the viability of distribution system components, distributed water quality, and health of long-term consumers of desalinated water supplies remains for the most part unknown.

Figure A.1 presents a general flow diagram of a membrane process with an example post-treatment chemical feed sequence. The membrane system assumes pretreatment with cartridge filtration and energy recovery (not shown). RO, NF and EDR membrane treatment systems typically consist of pretreatment and post-treatment processes in addition to the membrane process. Most municipal plants have multiple membrane process trains installed in parallel, allowing flexibility in permeate (product water) production and ease of expansion. In some instances it is possible to bypass a portion of the raw water around the plant and blend that flow with the permeate stream to reduce the capacity of the membrane system, improve finished water stability, and minimize capital and operating costs (Bergman and Elarde 2005). The maximum allowable blend ratio is determined from an analysis of bypassed and permeate water qualities.

Post-treatment processes typically include disinfection and corrosion control, and can include degasification and/or air stripping processes if carbon dioxide and hydrogen sulfide gases are present in the permeate water. Post-treatment is needed for municipal water treatment before the membrane-treated water is delivered to the distribution system as finished water. Membrane processes also produce a residual concentrate stream that may require treatment prior to disposal or reuse, such as the removal of hydrogen sulfide and/or addition of dissolved oxygen prior to surface water discharge; however, this document considers only permeate stream post-treatment.

Osmotic Flow

The process of osmotic flow involves the natural tendency of molecules to move from a region of higher concentration to a region of lower concentration. This process applies to membranes as molecules will move across a semi-permeable membrane via diffusion. Figure A.2 illustrates the concept of osmotic flow across a semi-permeable synthetic membrane. The semi-permeable membrane allows the passage of water, but not ions (e.g., Na^+, Ca^{2+}, Cl^-) nor larger molecules (e.g., natural organic matter). Diffusion and osmosis are thermodynamically favorable and will continue until equilibrium is reached. Osmosis can be slowed, stopped, or even reversed if sufficient pressure is applied to the membrane from the ‘concentrated’ side of the membrane. RO occurs when the water is moved across the membrane against the concentration gradient, from lower concentration to higher concentration.

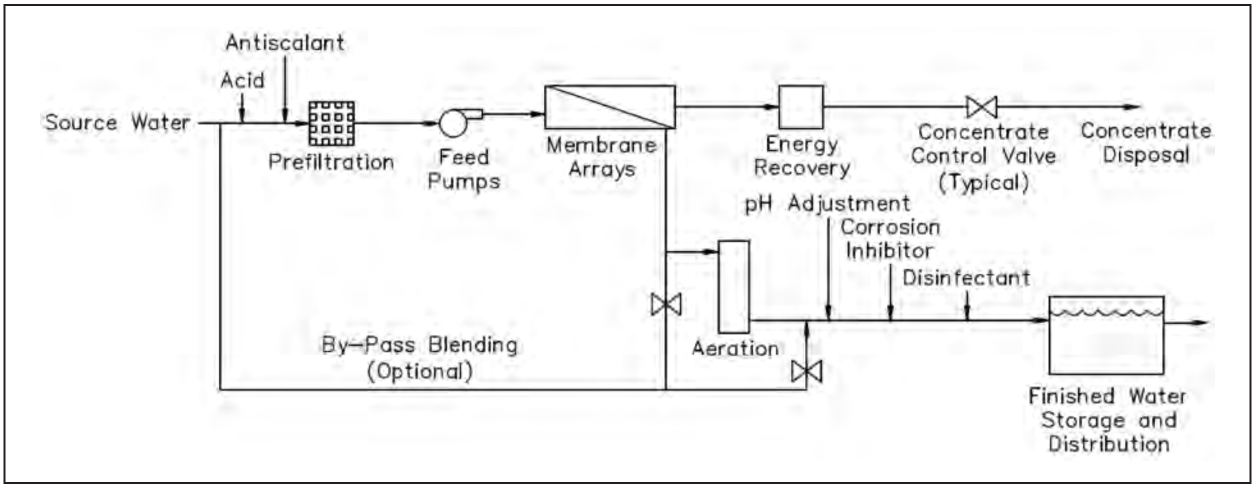


Figure A.1 Simplified membrane system flow diagram

To illustrate, imagine a semi-permeable membrane with fresh water on one side and a concentrated aqueous solution on the other side. If normal osmosis takes place, the fresh water will cross the membrane to dilute the concentrated solution. In RO, pressure is exerted on the side with the concentrated solution to force the water molecules across the membrane to the fresh water side. Thermodynamically, the osmotic pressure is defined as

$$\Pi = \frac{RT}{V_b}\ln(x_w) \tag{A.1}$$

with the osmotic pressure, Π, the molar volume of water, V_b, the mole fraction of water, x_w, and the ideal gas constant, R. In dilute solutions, the osmotic pressure can be estimated using van't Hoff's law, which was developed using the ideal gas law,

$$\Pi = \frac{n_s}{V}RT \text{ or } \Pi = CRT \tag{A.2}$$

with the total amount of solutes in solution n_s [moles], total concentration of solutes C [moles/L], and the volume of solvent V. Considering the dissociation of ions in solution, van't Hoff's equation is typically shown as:

$$\Pi = i\varphi CRT \tag{A.3}$$

with i representing the dissociation constant, which is equal to the number of ions and molecules per mole of solute produced by the dissolution of the solute, and where φ represents a correction factor for non-ideal behavior.

As a general rule of thumb the osmotic pressure of brackish water can be estimated by anticipating that for every 100 mg/L of total dissolved solids present in the feed water, one psi of osmotic pressure will be present within the membrane feed channel:

$$\Pi = [TDS, mg/L]\frac{1psi}{100mg/L\ TDS} \tag{A.4}$$

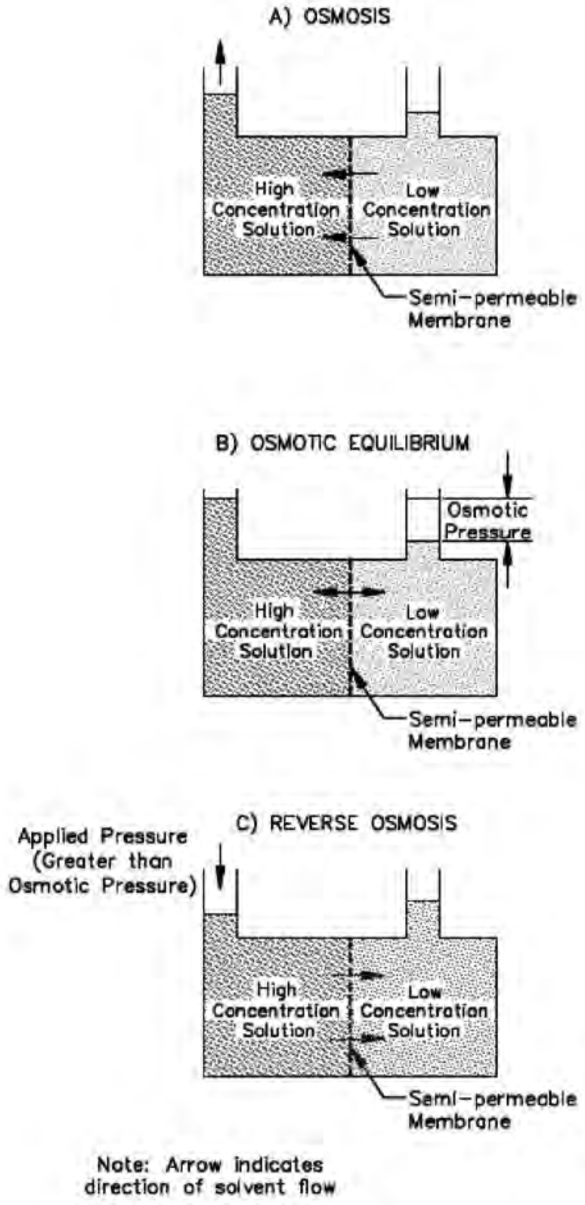


Figure A.2 Principles of osmostic flow

For a general estimate of the osmotic pressure of seawater, it can be assumed that an NaCl solution of equal total dissolved solids concentration is approximated as (Fritzmann et al. 2007):

$$\Pi = \frac{8bar}{wt\%_{NaCl}} \tag{A.5}$$

It should be noted that the actual osmotic pressure of seawater has been shown to be approximately ten percent than that of a solution of sodium chloride that is equal to the total dissolved solids concentration, due the presence of higher molar mass species that are present in the seawater (AWWA 1999). The permeate water quality is thus a function of diffusion of salt across the membrane and its associated osmotic pressure gradient, the transmembrane pressure, water recovery, and mass transfer of solute and water with respect to membrane material. These parameters will affect downstream quality and hence post-treatment processes.

Permeate Concentration

There are many different theories and models describing mass transfer in diffusion controlled membrane processes (Zhao and Taylor, 2004; Zhao et al. 2004, Zhao and Taylor, 2005, AWWA 2007), however a few basic principles or theories are used to develop most of these models. These are convection, diffusion, film theory and electro-neutrality. These principles or theories could be used to group models into linear diffusion models, exponential diffusion models and coupling models.

The homogeneous solution diffusion model is the basic model for describing the performance of membrane system (Weber 1972) where the water mass transfer flux is proportional to the pressure differential across the membrane (Kedem and Katchalsky 1958). One of the earliest published models describing the permeate concentration resulting from diffusion controlled mass transport for operating municipal NF and RO processes was developed at the University of Central Florida in the late 1980's (Taylor and Jacobs, 1996). The permeate concentration of a membrane processes can be predicted using several key mass transfer and membrane parameters, and is useful for determining post-treatment requirements. A basic element flow and mass balance diagram is shown in Figure A.3. There are many different theories and models describing mass transfer in diffusion controlled membrane processes, however a few basic principles or theories are used to develop most of these models. Figure A.3 shows a simplified diagram of mass transport in a synthetic membrane.

The basic equations used based on the homogeneous solution diffusion model (HSD) are shown in Equations A.6 through A.10.

$$J = k_W(\Delta P \Delta \Pi) = \frac{Q_p}{A} \tag{A.6}$$

$$J_i = k_i \Delta C = \frac{Q_p C_p}{A} \tag{A.7}$$

$$r = \frac{Q_p}{Q_f} \tag{A.8}$$

$$Q_f = Q_c + Q_p \tag{A.9}$$

$$Q_f C_f = Q_c C_c + Q_p C_p \tag{A.10}$$

where J = Water flux (L^3/L^2t)
J_i =Solute flux (M/L^2t)
k_w = Solvent mass transfer coefficient (L^2t/M)
k_i = Solute mass transfer coefficient (L/t)
ΔP = Pressure gradient (L), ($(P_f + P_c)/2 - P_p$)
$\Delta\pi$ = Osmotic pressure (L)
ΔC = Concentration gradient (M/L^3), ($(C_f + C_c)/2 - P_p$)
Q_f = Feed stream flow (L^3/t)
Q_c = Concentrate stream flow (L^3/t)

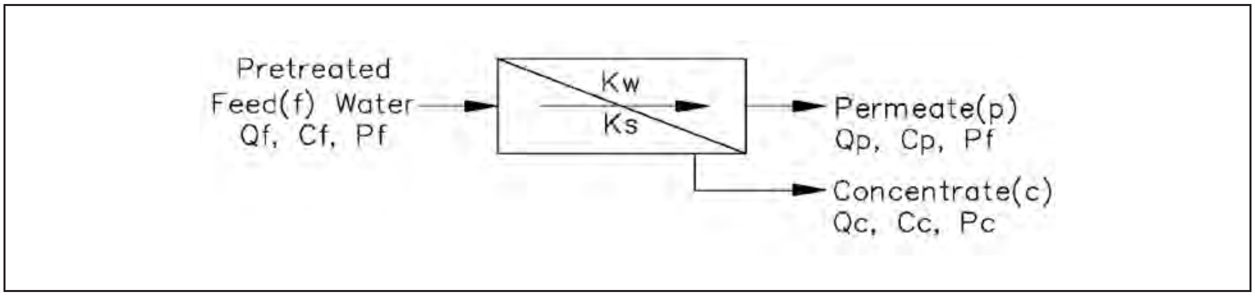


Figure A.3 Basic diagram of mass transport in a membrane

Q_p = Permeate stream flow (L^3/t)
C_f = Feed stream solute concentration (M/L^3)
C_c = Concentrate stream solute concentration (M/L^3)
C_p = Permeate stream solute concentration (M/L^3)
r = recovery
A = Membrane area (L2)
Z = Combined mass transfer term

If ΔC is defined as the difference of the average feed and brine stream concentrations and the permeate stream concentration, then Equation A.11 can be derived from Equations A.6 and A.10 (Duranceau, Mulford and Taylor 1992). This model can be described as a linear homogenous solution diffusion model in that it predicts solute flow is diffusion controlled and solvent flow is pressure (convection) controlled. Equation A.11 can be simplified by including a Z term which incorporates the effects of the mass transfer coefficients, pressure and recovery into a single term.

$$C_p = \frac{k_i C_f}{k_w(\Delta P - \Delta\Pi)\left(\frac{2-2r}{2-r}\right) + k_i} = Z_i C_f \tag{A.11}$$

Although this is a simple model, it does allow the effect of five independent variables on permeate water quality to be considered. If pressure is increased and all other variables are held constant then permeate concentration will decrease. If recovery is increased and all other variables are held constant, then permeate concentration will increase. These effects may be difficult to implement if an existing membrane array is considered, for it is not possible to increase recovery without increasing the permeate concentrate in such an environment. However, it is possible to increase pressure without varying recovery when arrays are designed. Different membranes may have different mass transfer characteristics. Using a membrane with a lower molecular weight cutoff would decrease the permeate concentration, although the solvent and solute MTCs would need to be considered before such a result could be obtained.

The diffusion-based model represented by Equation A.11 can be modified by the incorporation of film theory which assumes that the solute concentration exponentially increases from the center of the feed stream channel towards the surface of the membrane and diffuses back into the bulk stream, and can be modeled with the development of the homogenous solution diffusion model using concentration polarization. This model predicts that concentration at the membrane surface is higher than in the bulk of the feed stream. Such effects are documented in the literature and the model shown in Equation A.12 accounts for this phenomenon.

$$C_p = \frac{C_f K_S e^{F_w/k}}{K_W(\Delta P - \Delta\pi)\left(\frac{2-2R}{2-R}\right) + K_S e^{F_w/k}} \tag{A.12}$$

Using this approach, an integrated solution diffusion model can be developed for low-salinity RO and NF source waters based on the diffusion model. The concentration increment along the membrane channel is illustrated by finite units with respect to *R* (recovery) as shown in Equation A.14. Recall that:

$$\Delta\Pi = k_{TDS} \times \Delta C_{TDS} \tag{A.13}$$

and hence an integrated solution diffusion model can be developed based on the diffusion model. The concentration increment along the membrane channel is illustrated by finite units with respect to *R* (recovery) can be expressed as:

$$\frac{dC}{C} = \frac{F_w dR}{(F_w + K_s)(1-R)} \tag{A.14}$$

In Equation A.14, F_w represents water flux and K_s is the water mass transfer coefficient (MTC). Water is driven through the membrane by pressure (convection), whereas mass transfer of most inorganic and some organic solutes are diffusion controlled. Consequently, a simplification using the average bulk pressure of inlet and outlet pressure was made for model development as data was taken full or pilot scale plants that utilized spiral wound membranes. The osmotic pressure in a low-pressure NF or RO membrane permeate stream can be neglected since TDS in the permeate stream contributes very little to osmotic pressure for NF or RO for low-salinity water. The ratio of solutes in membrane bulk solution was assumed as fixed. Therefore, the water flux can be expressed as shown in Equation A.15, where *C* is concentration of one specific component (e.g., sodium), k_1 is the corresponding factor that relates *C* to osmotic pressure, and k_1C represents the osmotic pressure at the feed stream as it passes across the membrane channel.

$$F_w = K_w(\Delta P - \Delta\Pi) = K_w(\Delta P - k_1 C) \tag{A.15}$$

Combining Equation A.14 with A.15 provides the expression given in Equation A.16:

$$\int_{C_{Fo}}^{C_c} \frac{dC}{C} = \int_0^R \frac{[K_w(\Delta P - k_1 C)]\,dR}{\{[K_w(\Delta P - k_1 C)] = K_s\}(1-R)} \tag{A.16}$$

Integration under the boundary condition *C* from inlet C_{f0} to C_c as recovery increases from 0 at the inlet 0 to *R* at the outlet, results in Equation A.17:

$$\left(\frac{C_c}{C_{F0}}\right)^{\left(1+\frac{K_s}{K_w\Delta P}\right)}\left(\frac{\Delta P - k_1 C_{f0}}{\Delta P - k_1 C_c}\right)^{\frac{K_s}{K_w\Delta P}} = \frac{1}{1-R} \tag{A.17}$$

A solute mass balance of the membrane system is shown in Equation A.18.

$$C_c = \frac{C_{f0} - RC_P}{1-R} \tag{A.18}$$

Incorporation of Equation A.18 into Equation A.17 results in Equation A.19, which is rearranged into the final model or Equation A.20, where $\Delta\prod_{\text{in}}$ is bulk osmotic pressure at membrane inlet, $\Delta\prod_{\text{out}}$ is bulk osmotic pressure at membrane outlet with k_2 being defined as the osmotic pressure correcting coefficient.

$$\left[\frac{C_{f0} - RC_P}{C_{f0}(1-R)}\right]^{\left(1+\frac{K_s}{K_w \Delta P}\right)} \left(\frac{\Delta P - k_1 C_{f0}}{\Delta P - k_1 C_c}\right)^{\frac{K_s}{K_w \Delta P}} = \frac{1}{1-R} \tag{A.19}$$

and

$$C_P = \frac{C_f}{R}\left\{1 - [k_2(1-R)]^{\frac{K_s}{K_w \Delta P + K_s}}\right\} \tag{A.20}$$

where

$$k_2 = \left(\frac{\Delta P - k_1 C_c}{\Delta P - k_1 C_{f0}}\right) = \frac{\Delta P - \Delta \Pi_{out}}{\Delta P - \Delta \Pi_{in}} \tag{A.21}$$

Note that $K_1 C_1$ is osmotic pressure as approximated by a TDS correlation to osmotic pressure. The model is shown in Equations A.20 and A.21, and incorporates a general osmotic pressure correction factor that was estimated using a TDS or conductivity relationship with osmotic pressure. A final model is shown in Equation A.22 and uniquely predicts permeate stream concentration of diffusion controlled solutes using a continuous correction for osmotic pressure:

$$C_P = \frac{C_f}{R}\left\{1 - \left[\frac{\Delta P - k_{TDS} \times TDS_c}{\Delta P - k_{TDS} \times TDS_f}(1-R)\right]^{\frac{K_s}{K_w \Delta P + K_a}}\right\} \tag{A.22}$$

where k_{TDS} = 69 Pa/(mg/L TDS), or 0.01 psi/(mg/L TDS), or determined experimentally.

AN OVERVIEW OF PERMEATE POST-TREATMENT

Permeate Post-Treatment

Introduction

Desalination will result in the production of water having low dissolved solids content that can and will cause internal corrosion, and may not be fit for human consumption. Pure water is considered a reactive chemical: when air is dissolved in extremely pure water, the resultant solution is very corrosive. Water that contains little to no hardness would be considered unhealthy for potable use and water that contains no dissolved oxygen may be offensive and taste flat. Consequently, post-treatment of membrane desalinated water is required prior to storage and distribution for municipal water purveyors, and must include disinfection.

Treatment processes downstream of the synthetic membrane processes RO, NF or EDR facilities are referred to as post-treatment processes. The water produced from the RO, NF and EDR membranes used to desalt water supplies usually requires some form of post-treatment because the permeate water from these membrane technologies can be corrosive because they have been desalted and purified. The water produced by a membrane process will require additional treatment, which may consist of several difference unit operations, before it is suitable for potable water use (Taylor et al., 1989; Byrne, 1995; Duranceau, 2001). Factors that should be included when referring to the quality of desalinated waters include the chemical and biological stability of water and its interaction with the distribution system (Lahav and Birnhack 2007; Taylor et al. 1989).

Permeate Conditioning and Blending

A recent overview of the current state of 62 full-scale RO/NF plants conducted by Burbano and others (2007) for plants greater than one-million gallons per day of capacity, used for either seawater desalination, brackish water desalination (including groundwater, surface water and agricultural runoff), or wastewater reclamation provides an insight into post-treatment practices. All of the surveyed facilities reported using at least one post-treatment method for permeate conditioning and corrosion control. These included such methods as caustic addition (31%), blending with raw, semi-treated or finished water (29%), degasification/decarbonation (25%), and addition of corrosion inhibitor (14%). Most of the brackish water RO plants responding to the survey reported using degasification/decarbonation and caustic 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. Other reported disinfection methods included the use of chloramine (24%) and ultraviolet irradiation (4%).

Desalinated waters are commonly blended with small volumes of more mineral-rich waters to improve their acceptability and particularly to reduce their aggressive attack on materials (WHO, 2004). Blending water should be fully potable; where seawater is used for this purpose, the major ions added are sodium and chloride. This does not contribute to improving hardness or ion balance, and only small amount, no more than 3 percent, can be added without leading to problems of acceptability. Blended waters from coastal and estuarine areas may be more susceptible to contamination with petroleum hydrocarbons or algal toxins, which could give rise to taste and odor problems. Some ground or surface waters, after suitable treatment, may be employed for blending in higher proportions and may improve hardness and ion balance.

Municipal Methods

For municipal water systems, post-treatment is always required for the permeate flow stream before distribution to the water community (AWWA 2007). The choice and sequence of post-treatment operations are typically determined by regulatory requirements, which can impact the design of the system and finished water quality criteria. The need for post-treatment typically depend on factors which can be grouped into three general water quality related categories:

- Chemical Stability
- Microbiological Stability
- Palatability and Customer Acceptability (color, odor, taste).

Post-treatment generally must address the aggressive nature (low pH) of the desalted water. Pretreatment conditions must also be evaluated when considering post-treatment to ascertain how pretreatment (such as acid addition) will affect desalted water quality. Post-treatment to supply drinking water commonly includes permeate water pH adjustment for corrosion control and chemical addition for disinfection.

For brackish groundwater and surface water supplies, pH and alkalinity adjustment for stabilization, corrosion control and disinfection are typically required. Seawater supplies may or may not require similar post-treatment, depending on whether or not the water is from an open intake or wells. In addition to chemical treatment, blending with raw, or other water supplies feeding the distribution system, can produce non-corrosive water. Many facilities pump desalinated water directly into the distribution system without being mixed or blended with other finished water supplies raising concerns regarding distribution system water quality (Fayad 1993; Imran et al. 2005).

Non-aggressive water can be produced by the addition of alkaline chemicals and, in some cases, other chemicals, or blending with raw or other water supplies that may also feed the distribution system. Often corrosion inhibitors are added to further reduce the corrosion potential of the finished water. Seawater desalting post-treatment will often rely on a lime contactor for stabilization particularly if blending is not available on-site. The addition of lime is exothermic, and post-stabilization deposition may occur downstream of the lime contactor if dosage controls are not diligently maintained. Furthermore, the addition of lime other than a food-grade quality can impart turbidity to the downstream distributed water.

Several chemicals may be added to the finished water to increase pH, bicarbonate alkalinity or dissolved inorganic carbon (DIC), calcium, and orthophosphate (phosphate alkalinity). Lime (calcium hydroxide), soda ash (sodium carbonate), calcium chloride, sodium bicarbonate, caustic soda (sodium hydroxide) and blended or zinc orthophosphates can be used for post-treatment. However, many of these chemicals, such as lime, calcium chloride, sodium bicarbonate are shipped as a dry chemical which requires operators to prepare chemical feed stock solutions prior to use. The use of dry chemical feed systems has several disadvantages (Bergman and Elarde 2005): storage and handling equipment requirements are increased; operation and maintenance requirements are increased; incomplete mixing and/or impurities (fillers) in the dry chemicals will add turbidity.

Consequently, the use of gas and liquid supplied chemicals for post-treatment pH, alkalinity and corrosion inhibitor addition are often employed at desalting facilities. Carbon dioxide, sodium hydroxide, and phosphate-based corrosion control inhibitors are widely used in the United States for ease of use and delivery, unless hardness addition is required.

Water Quality Considerations

Essential Elements

Desalinated water often contains lower than usual concentrations of other ions commonly found in water, some of which are essential elements. Water typically contributes a small portion of these, and most dietary intake is through food. Exceptions include fluoride, and declining dental health has been reported from populations consuming desalinated water with very low fluoride content where there is a moderate to high risk of dental caries (WHO 2003, 2005).

Concern has also recently been expressed about the impact of extremes of major ion composition or ratios for human health. There is limited evidence to describe the health risk associated with long-term consumption of such water, although mineral content may be augmented by stabilization processes typically used by utilities practicing desalination (WHO 2003, 2005). Seawater is rich in ions such as sodium, chloride, magnesium, calcium, bromide and iodide, but low in some essential ions like zinc, copper, chromium and manganese.

Water Quality Parameters and Stability

Permeate streams from sea water and brackish water desalting processes are primarily a dilute solution of sodium chloride. To provide stability to water, and to prevent corrosion (metal release) of piping systems and domestic plumbing, post-treatment is necessary to return some calcium hardness and bicarbonate alkalinity to the water. In many situations, post-treatment also includes the removal of carbon dioxide to raise the pH, hydrogen sulfide removal when required, and the addition of fluoride which is removed during the desalting process. Improper post-treatment of permeate can become problematic with regards to corrosion control, disinfection residual, and can result in taste and odor complaints.

As a result, corrosion control is one of the greater priorities when either directly pumping desalted finished waters into the distribution system or when blending different water sources from membrane process. The constituents of concern when establishing a post-treatment process include the pH, which will be dependent upon the buffering capacity and bicarbonate alkalinity, calcium, sulfate and chloride, dissolved oxygen, boron, total dissolved solids concentration and corrosion indices. These parameters are interrelated in the final treatment process selected for post-treatment, depending on application and source water (i.e., ocean surface versus brackish groundwater supplies).

pH. Various studies have been done to correlate the effect of pH on corrosion in pipes. The pH in a system is directly related to the alkalinity, $Ca^{2+,}$ and CCPP in the system. Lahav and Birnhack (2007) stated that the pH determines the buffer capacity of the water sources. When different water sources are blended the chemical stability of the blend is significantly determined by the buffering capacity of the original waters. A higher pH will usually result in a lower buffer capacity, noted to be associated with low corrosion rates and prevention of red water episodes; however most studies have shown pH to be an isolated single parameter.

Lahav and Birnhack (2007) states that Imran did a study that showed that pH has no effect on the rate of corrosion or on the rate of iron release to the water as long as the water was supersaturated $LSI > 0$ for the pH range $7.8 < pH < 8.4$. The use of Langlier Saturation Index to support a determination of corrosivity, although not widely used for this purpose, is relied upon by many water purveyors as a reference point and is often included on desalination plant monthly operations reports. However, according to McNeill and Edwards, the LSI has been improperly applied as a cure-all method for solving corrosion problems since it was first proposed in 1936, and it should not be singularly relied upon as a method for controlling internal corrosion. As noted by McNeill and Edwards, the AWWA manual on corrosion states "*In light of much empirical contradicting of the presumed connection between the LSI and corrosion the practice should be abandoned*." However, despite the criticisms offered by McNeill, Edwards, and others it is fact that most, if not all, regulatory agencies within the USA require water purveyors to monitor, document and report the LSI on water purveyor monthly operating reports, particularly where advanced processes are used in part or entirely for treatment, and are deemed important with regards to utility administrator decision-making and regulatory monitoring purposes. In addition, the LSI is used to meet desalted water post-treatment goals according to the Gulf Drinking Water Quality Standards (GDWQS 1993).

Alkalinity. Alkalinity in water is a measure of the general buffering capacity or stability of the water. Increasing the alkalinity generally leads to lower corrosion rate and results in fewer changes in pH of distributed water; however, excess alkalinity can cause excessive scale deposition where calcium may be present. Alkalinity is thus directly related to the buffering capacity of water and is considered an important parameter affecting the pH, and is represented by the equation:

$$\text{Alkalinity} = 2[CO_3^{2-}] + [HCO_3^-] + [OH^-] - [H^+] \tag{A.23}$$

Alkalinity depends on the concentration of bicarbonate, carbonate, and hydroxide ions in water. According to Lahav and Birnhack (2007) for a given pH value, the higher the alkalinity value, the higher the ability of the water to withstand a change in pH due to release of H^+ and OH^- ions to the water. A higher alkalinity at a given pH translates into a higher dissolved inorganic carbon (DIC) concentration of the carbonate species (CO_3^{2-}). However, too high of an alkalinity at higher pH levels may accelerate lead and copper metal release (Duranceau et. al, 2004c; Taylor et al. 2005).

It is also known that red water prevention can be accomplished by maintaining the alkalinity in the system when considering a subsequent pH shift if treatment was to be employed. Non-stabilized finished water can experience fluctuations in pH in the distribution system as scale is deposited (scale) or dissolved (corrosion), particularly when taking into account disinfection where chlorine may be present to react with the constituents in the water and infrastructure. It is desirable to maintain the alkalinity concentration in distributed water above one to one and one-half millequivalent of alkalinity, or 30 to 60 mg/L (as calcium carbonate). Maintaining a moderate alkalinity is important in treated water with a negative saturation index as described by corrosion indices discussed herein.

While hydroxide alkalinity will increase the finished water pH and non-carbonate alkalinity, carbonate and bicarbonate alkalinity are still required to produce a Calcium Carbonate Precipitation Potential within a desired range of values in order provide adequate buffering capacity, and prevent pH variations within the system. Post-treatment methods used to recovery or increase alkalinity in desalinate permeate include:

- Addition of caustic soda or lime to permeate containing carbonic acid;
- Addition of carbonic acid followed by the addition of caustic soda or lime;
- Addition of sodium carbonate or sodium carbonate;
- Calcium carbonate through the use of limestone contactors.

Hardness. Calcium and magnesium are important minerals necessary for human health, and is also important with respect to calcium carbonate film deposition on internal piping surfaces that comprise the water distribution system. Blending of native water supplies, or bypass blending of raw water supply around the membrane process can assist to increase the hardness of permeate. However, when chloride or sodium concentrations are high in the raw or native blend water, the ability to blend is limited. Slaked lime is often added to desalted seawater permeate to provide calcium and alkalinity in the form of hydroxide, in addition to providing pH adjustment. If lime is used for post-treatment to increase hardness, recarbonation may also be required to fully dissolved residual lime. Post-deposition of lime in downstream appurtenances is possible and must be monitoried. Although limestone filters of 8 to 12 foot bed depth have been suggested for permeate post-treatment, they have been limited in use in the United States and are more often encountered in Europe, the Pacific Rim, and the Middle East, often in conjunction with carbonic acid addition (AWWA 2007).

Dissolved Oxygen. The oxygen concentration can have varying effects on iron corrosion. The corrosion rate increases with increasing dissolved oxygen. Low dissolved oxygen can result in anaerobic microbial processes in service lines, resulting in offensive odors. Perceived "flatness" of water has also been associated with low dissolved oxygen levels. Dissolved oxygen is also responsible for the ability of buffering ions, including phosphates to inhibit corrosion (McNeill and Edwards 2001). White water complaints can occur when water is saturated with dissolved oxygen within the water column under pressure, and will manifest itself when released from the faucet.

Brackish Water Post-Treatment Considerations

With regards to groundwater RO and NF supplies that are typically anaerobic, entrained gases such as carbon dioxide, hydrogen sulfide and methane (if present) are removed downstream of the membrane process before final pH adjustment and disinfection (Duranceau 2001). Removal of these gases is normally accomplished by stripping in a forced-draft packed column. In the most cases, carbon dioxide must be removed to stabilize the RO product water. If hydrogen sulfide is present, air stripping of the product water is usually done to control odor and minimize the amount of disinfectant (e.g., chlorine). The final product-water pH is often adjusted by caustic soda, soda ash, or lime. As a result, the primary desalination water plant post-treatment unit operations for potable water supplies reliant upon brackish groundwater are the following (AWWA 2007; Duranceau, 1993):

1. Carbon dioxide removal (degasification or decarbonation);
2. Hydrogen sulfide removal (stripping) and odor control treatment (scrubbing);
3. Alkalinity recovery, pH adjustment, stabilization and corrosion control; and,
4. Disinfection.

Decarbonation. Dissolved carbon dioxide (or "free CO_2") exists naturally in many water sources, particularly in groundwater. Free carbon dioxide puts an ionic load stress on ion removal methods such as anion resin beds, continuous deionization (CDI) systems, and can internal corrosion within metallic distribution systems if not properly treated.

Carbon dioxide, along with nitrogen and oxygen, comprise the majority of atmospheric gasses. Water contains these gases in solution, following Henry's Law of gas solubility that defines a proportional relationship between the amount of a gas in a solution and its partial pressure in the atmosphere. Carbon dioxide, however, is an exception to Henry's Law because it reacts with the water to form carbonic acid, which then ionizes into hydrogen and bicarbonate ions. Since the bicarbonate ions are not subject to Henry's Law, only a small amount of it can be released by aeration. Carbon dioxide in the water that does not form bicarbonates is "uncombined" and can be removed by aeration.

Carbon dioxide is easily removed from brackish permeate water with the use of aeration, often referred to as degasification or decarbonation. The pH of the permeate water will determine the amount of carbon dioxide available to be removed from the water, as shown in Figure A.4. The pH of the water affects equilibrium between bicarbonate ions and carbon dioxide. At a pH below

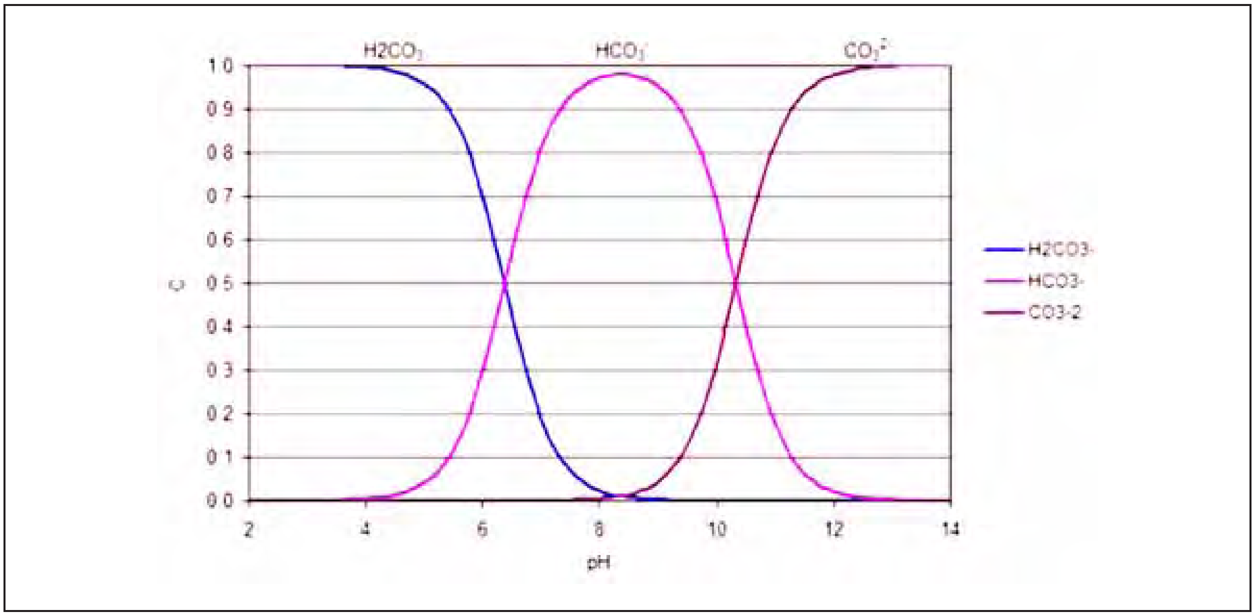


Figure A.4 Effect of pH on carbonate species as a fraction of concentration

approximately 4.5, all of the carbon dioxide dissolved in the water is present as a gas. At a pH of about 8.5, all the carbon dioxide is ionized. For this reason, decarbonation by air stripping is only effective at low pH with the pH reduction resulting from prior process or acid addition. Carbon dioxide exists in equilibrium with other carbonate species as defined by the following equations:

$$CO_2\ (gas) + H_2O = H_2CO_3\ (gas) \qquad pK_1 = 2.8 \qquad (A.24)$$

$$H_2CO_3\ (gas) = H^+ + HCO_3^-\ (aq) \qquad pK_1 = 6.3 \qquad (A.25)$$

$$HCO_3^-\ (aq) = H^+ + CO_3^{2-}\ (aq) \qquad pK_2 = 10.3 \qquad (A.26)$$

Hydrogen Sulfide Stripping. Many of the brackish groundwaters used as feed streams to RO or NF plants contain hydrogen sulfide. Hydrogen sulfide dissociates in water according to the following equations:

$$H_2S\ (gas) = H^+ + HS^-\ (aq) \qquad pK = 7 \qquad (A.27)$$

$$HS^{1-}(aq) = H^+ + S^{2-}\ (aq) \qquad pK = 14 \qquad (A.28)$$

Conventional pretreatment (acid addition, scale inhibitors, cartridge filtration) will not remove hydrogen sulfide nor will the membrane process, and hydrogen sulfide will permeate the membrane as a gas. Aeration and oxidation are the two primary means for removing hydrogen sulfide; incomplete chemical reactions in the process are often responsible for formation of polysulfide complexes and elemental sulfur, which manifest themselves as turbidity in the finished water (Lyn and Taylor 1992). As shown in Equation A.27 and represented in Figure A.5, since at pH of 7 only 50 percent of hydrogen sulfide exists in the gas form and is available for stripping pH adjustment is normally used to improve removal efficiency. The pK for hydrogen sulfide is 7, such

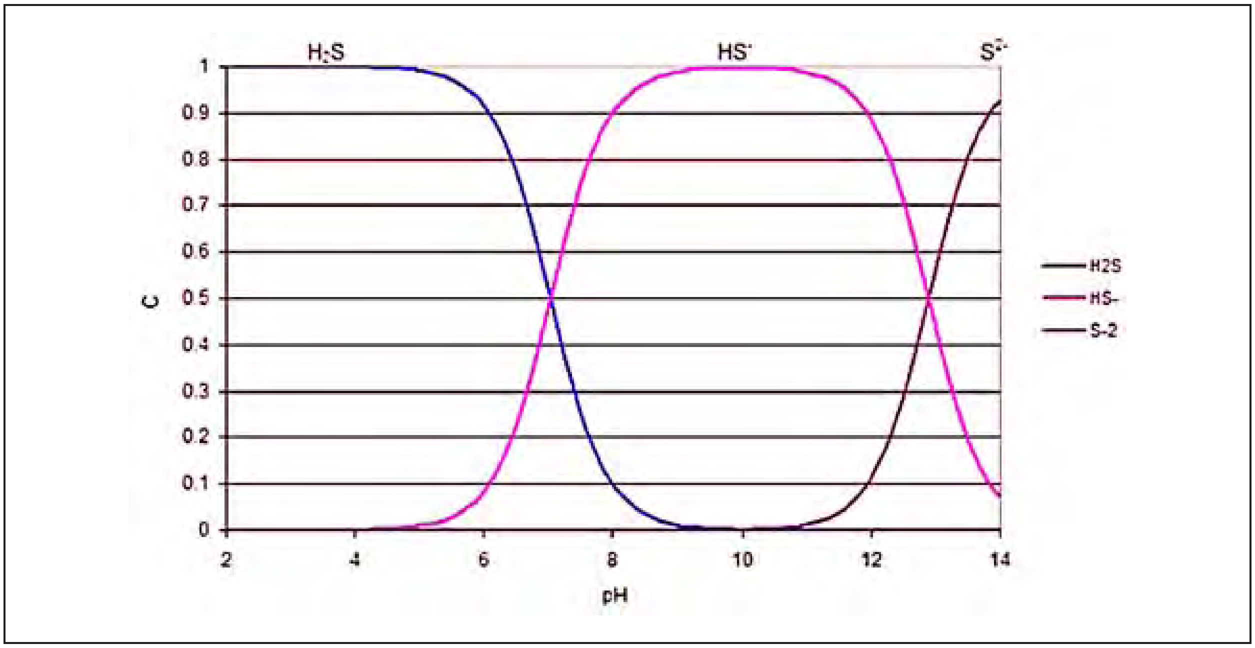


Figure A.5 Effect of pH on hydrogen sulfide species as a fraction of concentration

that hydrogen sulfide gas can be completely removed at pHs below 6.3 without the formation of turbidity (elemental sulfur). However, all of the carbon dioxide that is dissolved in the permeate water will also be removed.

Alkalinity, pH Adjustment, Stabilization, and Corrosion Control. Utilities generally determine the composition of the product water and post-treatment is determined based on their regulatory and water quality standards. Problems that may occur within distribution system if water is not treated include corrosion within the pipes, which can lead to red water going to the consumers tap.

The alkalinity of water is a measure of its capacity to neutralize acids. Bicarbonates represent the major form of alkalinity in water, since they are formed in considerable amounts from the action of carbon dioxide upon basic materials in the soil. Stabilizing membrane produced permeate water so that corrosion problem do not occur within the distribution system include pH and alkalinity adjustments, and the used of corrosion inhibitors. Blending waters are also used to lower the effect of adding desalted water directly in to distribution system.

Temperature, pH and the concentration of bicarbonate are important in the formation of calcium carbonate in water (Equation A.29):

$$Ca^{2+}\text{ (dissolved)} + 2(H_2CO_3)_2\text{ (dissolved)} \Leftrightarrow CaCO_3\text{ (solid)} + H_2O + CO_2\text{ (gas)} \qquad (A.29)$$

Unless carbonate is added or a significant amount of alkalinity passes the membrane, there will be no carbonate (alkalinity) buffering in permeate, a possible problem with respect to stabilization and corrosion control even if pH adjustment with sodium hydroxide is practiced. However, it is common practice in brackish water desalting to adjust the pH of the permeated water with sodium hydroxide and include the addition of a corrosion control chemical, typically a blended or zinc orthophosphate-type chemical.

If the desalination facility is treating brackish groundwater supplies, better methods are required to resolve the common post-treatment issue concerning alkalinity adjustment: an increase in the pH entering the tower prior to air stripping to recover 1 to 2 meq/L of alkalinity could be beneficial if allowed. However many facilities will not provide additional unit operations between the membrane process and the air stripper process. The use of carbonic acid pH adjustment, however, prior to air stripping of hydrogen sulfide has proven beneficial with regards to buffering loss of finished water (Duranceau, 1999; Lovins et al. 2004b).

Disinfection. Post-treatment disinfection is normally accomplished with chlorine, used as a primary disinfectant. However, chloramines, ozone and chlorine dioxide can also be employed to serve as chemical disinfectants in water treatment to inactivate pathogens, viruses, coliform and biofilm. An unintentional use of chemical disinfection in water treatment is the formation of chlorinated disinfection by-products (DBPs), potential carcinogens and a matter of public concern (Rook 1977, Sittig 1985, USEPA 2007); in addition, brominated and iodinated DBPs have also been identified in water distribution systems (Krasner et al. 1989, Hua, Reckhow and Kim 2006).

As in conventional treatment, disinfection is required, but the chlorine demand is greatly reduced by membrane desalting process, resulting in minimal formation of disinfection byproducts (Taylor et al. 1989). However, if the desalting process allows the blending or bypass of water that contains disinfection byproduct (DBP) precursors, then chloramines, or some additional post-treatment of the blended water (or a reduction in the quantity bypassed or blended) may be required to comply with DBP drinking-water quality standards.

Desalinated waters constitute a relatively easy disinfection challenge because of their low TOC and particle content, low microbial loads and minimal oxidant demand after desalination treatments. Turbidity is not likely to affect chemical disinfectant performance by since turbidity values of desalinated water are relatively low. Post-treatment with lime can cause an increase of inorganic turbidity that would not interfere with disinfection; use of food-grade lime aids to limit the amount of inorganic turbidity imparted to the water. The target levels of inactivation for pathogens remaining in desalinated waters can readily be achieved by appropriate disinfection processes. It is noteworthy to add that due to the breakthrough of bromide, it can be difficult to maintain chlorine residuals in the distribution system as stable as regular surface or groundwater.

Chorine and the corresponding base can be simultaneously applied to the permeate stream following alkalinity recovery (Duranceau 1993). If chlorine has been used for sulfide removal and excess chlorine has been used some disinfection may have been accomplished; however chlorine will react preferentially with sulfides and not form any free chlorine until the sulfide demand has been exceeded (Lyn and Taylor 1992). If chlorine and a base are added to the process stream before aeration, disinfection, oxygen addition and stabilization will occur.

Seawater Post-Treatment Considerations

The untreated permeate from seawater desalting facilities are highly aggressive and corrosive to water distribution components, pipeline systems, storage facilities and appurtenances. There are many different methods available for increasing the mineral and buffering content of desalinated seawater in an effort to produce a buffered water having a stable pH value with a slightly positive LSI (Withers 2005). Lime or limestone filtration and carbon dioxide polishing (to achieve permeate water quality goals) are often employed throughout the world to recarbonate desalted seawater supplies. However, the use of hydrated lime can result in excessive formation of finished water turbidity, which may impact compliance with the SDWA Surface Water Treatment

Rules should the seawater facility be permitted as a surface water supply. Furthermore, process control issues could arise if hydrated lime is used for permeate having such low buffering capacity, possibly resulting in variable pH and LSI entering the distribution system. The use of a 3 percent lime slurry solution strength has been shown to be effective (Withers 2005). Should the seawater feed to the desalting process is acidified as a part of the pretreatment process, then carbon dioxide will exist in the permeate, assuming acid dosage was employed for calcium carbonate precipitation fouling control. Consequently, the selection of an appropriate desalted seawater post-treatment method, or methods, remains a site-specific consideration. Alternative treatments reported for use in seawater desalination post-treatment applications include (Withers 2005):

1. Addition of carbon dioxide and excess lime;
2. Filtration of carbon dioxide dosed permeate through limestone bed contactors;
3. Application of sodium carbonate and hydrated lime;
4. Application of sodium bicarbonate and calcium sulfate;
5. Application of sodium bicarbonate and calcium chloride;
6. Blending with a native low-salinity water source or by-pass blending.

Remineralization can be categorized into a series of four treatment processes: (1) chemical addition without lime or limestone; (2) carbon dioxide addition followed by limestone bed contactors for dolomitic dissolution, (3) carbonic acid addition followed by lime dosing; blending with a water containing high mineral content.

Regulatory Considerations

There are many regulations that apply to potable water. A thorough understanding of the regulations governing the particular application is required before a post-treatment design can be performed. Continuing advances in regulatory mandates and increasing demands related to aesthetic criteria for consumer water quality have driven the water community to seek new water supplies and treatment technologies that meet SDWA criteria. Foremost among regulatory constraints are disinfection requirements, disinfection by-product formation and corrosion control regulations. Consumers have become aware of regulatory violation through mandated public notification and Consumer Confidence Reports (CCR), and they have always been aware of the appearance, taste and odor of drinking water. Increasing demands for additional water resources have required communities to seek alternative water supplies that may produce process streams that are not compatible with existing supplies. Potential water quality impacts of particular importance when addressing water quality compatibility involve: regulatory compliance; public health effects; the chemicals used to provide disinfection; and the factors affecting the corrosiveness of the water distributed to customers.

For example, desalination has to reduce typical seawater (approximately 32% salinity to an acceptable drinking water standard of below 500 mg/L total dissolved solids. In addition, regulations corresponding to the water distribution system also need to be taken into account, and include the Lead and Copper Rule (LCR), Disinfectant/Disinfection By-Products Rule (D/DBP), and Total Coliform Rule (TCR).

Evaluation of corrosion control is not as straightforward for lead and copper control at consumer taps as there are other regulated mandates other than the LCR, such as the D/DBP (organics) and TCR (disinfection) that are occurring simultaneously, and the multitude of changes that can occur in a water distribution system may mask any single change. Corrosion control is often implemented using chemical-type treatments based on dosing treatments within the treatment facility where the chemical feed systems rely on the use concentrated bulk chemical feed tanks. Locally the waters can be either corrosive or scaling, and as such, the distribution system is monitored for corrosion indices, the most common in use is the Langelier Saturation Index (LSI) despite the fact that recent work has shown that additional factors are more relevant to monitoring and maintaining corrosion control in a water system (Singley 1981).

Further, taste and odor concerns dominate the response of most water utilities to customer concerns, and although are regulated as Secondary Contaminants per the SDWA, the taste and odor of permeate is for the most part subjective. Taste refers only to sensations typically referred to as bitter, salty, sour and sweet, and is dependent upon the chemical substances present (Malleviale and Suffet 1987). Odor, like taste, depends on the chemical substances present in the water being consumed. Certain inorganic salts can produce tastes without odor, and as a result, permeate of desalinated water systems can appear to have a flat taste. If disinfectant is present, a perceived odor can also be noted. Customers have been known to register complaints to their water purveyor when a drastic change in water quality occurs, but will become accustomed to a new water quality given time, assuming the quality does not further change substantially (WHO 2004). Stabilization will reduce the perceived reactions to desalted permeate, in addition to providing its primary associated benefit related to addressing internal corrosion control concerns.

Lead and Copper Rule. The Lead and Copper Rule was promulgated by the USEPA on June 7, 1991 as a methodology to reduce lead and copper in drinking water. In the LCR, the USEPA has mandated that the most appropriate methods for reducing lead and copper are (1) water treatment for corrosion control in the distribution and plumbing systems and removal of lead and copper from source water, (2) replacement of lead service lines, and (3) public education (AWWA 1992a). The control of internal corrosion within the distribution system in desalted and/or blended waters is imperative to maintain compliance with the LCR and provide acceptable consumer confidence.

The major source of lead in drinking water is typically not the source water, but the corrosive action of the water on materials in plumbing systems. Newly installed tin-lead-soldered copper piping is often found to release appreciable amounts of lead into the drinking water plumbing system, and gradually decreases as the internal surfaces of the pipe age with time. Corrosion control measures acceptable to reduce lead and copper at the customer's tap under LCR are water chemistry control or use of corrosion inhibitors in the water treatment. Chemical control is typically accomplished via either/or pH adjustments using sodium hydroxide or other base, addition of alkalinity using calcium carbonate or soda ash, or use of inhibitors. Phosphate and silicate based corrosion inhibitors can also be used for corrosion control (AWWA 1992b).

From LCR monitoring studies (AWWA 1992a), optimal corrosion control water parameters (pH, calcium, alkalinity, conductivity, temperature, corrosion inhibitor concentration) are determined and the operating point for the water system is set. Permeate water without treatment can and will affect compliance with the LCR such that stabilization and treatment for corrosion control is required (Duranceau 2004b and Duranceau et al. 2004). Internal corrosion is a complex electrochemical phenomenon that cannot be eliminated, but can be controlled in a cost-effective manner. The most prominent corrosion by-products in drinking water are lead and copper. While iron oxides are the major corrosion by-products, lead and copper are the by-products of major concern; corrosion control strategies aim to limit lead and copper, the corrosion by-products of major concern, in drinking water. Water velocity, residence time, temperature, and water quality (pH, hardness, alkalinity, dissolved oxygen) can affect corrosion rates of common plumbing systems.

Few studies are available that demonstrate the direct impact of membrane permeate on compliance with the LCR. However, membrane softening processes have been shown to reduce the propensity of copper and lead metal release as compared to traditional water treatment for groundwater supplies. Duranceau (1999) showed that the implementation of a membrane softening facility for a groundwater supply in Dunedin, Florida resolved total trihalomethane issues as well as aid in the reduction of copper content in consumer taps.

Disinfection and Water Quality. Post-treatment disinfection is required in the United States and is normally accomplished with chlorine. The Total Coliform Rule (TCR) is the primary regulatory vehicle for monitoring the microbial stability of a distributed water and presence of potential pathogens by monitoring for TC as a surrogate of pathogen intrusion. As in conventional treatment, disinfection is required, but the chlorine demand is greatly reduced by the desalting process, resulting in minimal formation of disinfection byproducts (Taylor et al. 1989). Also, application of chloramines to desalinated waters having higher levels of bromide can result in the rapid loss of disinfectant residual in water conveyance systems (Agus et al. 2009).

However, if the desalting process allows the blending or bypass of water that contains disinfection byproduct (DBP) precursors, then chloramines, or some additional post-treatment of the blended water (or a reduction in the quantity bypassed or blended) may be required to comply with DBP drinking-water quality standards.

Desalinated waters present a relatively easy disinfection challenge because of their low TOC and particle content, low microbial loads and minimal oxidant demand after desalination treatments. Turbidity is not likely to affect chemical disinfectant performance since turbidity values of desalinated water are relatively low. Post-treatment with lime can cause an increase of inorganic turbidity that would not interfere with disinfection; use of food-grade lime aids to limit the amount of inorganic turbidity imparted to the water.

Almost no chlorine demand will remain following a RO or NF process. The chlorine will convert some of the recovered alkalinity to carbon dioxide which will be lost during aeration; however the pH should return to the stabilization pH as carbon dioxide will tend to be at equilibrium with the atmospheric carbon dioxide. The pH will closely approach pH_s with respect to calcium carbonate.

Chlorine addition to water will produce equal moles of hypochlorous acid and hydrochloric acid. The hypochlorous acid will partially ionize to hypochlorite ions as protons. The hydrochloric acid will completely ionize producing protons and chloride ions. One mole of protons will be produced for every mole of hydrochloric acid and every mole of hypochlorite ion produced. Consequently, the complete proton production during chlorination would be canceled by the addition of OH^- as shown above. Unlike seawater desalination which may require 1 to 2 mg/L of chlorine for disinfection, typical chlorine doses following a membrane softening NF process could range from 5 to 7 mg/L, and is dependent upon several factors including chlorine demand, bromide and TOC concentration, pH, temperature and dosage rate (Taylor et al. 1989).

Calcium deposition at injection points can result from poor design or installation, so one needs to make sure that chemical injection quills reach far enough into the flow for effective dilution, and that the materials of construction that are specified can handle forces of velocity, are hydraulically and chemically resistant.

Disinfection By-Products. Chlorination is the most common disinfectant in current use for post-treatment of desalinated permeate, followed by either chloramines or chlorine dioxide unit operations. When brackish or seawater permeate is chlorinated, bromoform and brominated haloacetic acids have been determine to be present (Agus et al. 2009). Less information is available of other haloorganic DBPs in desalination plants. DBPs identified in desalted permeate water include haloacetonitriles, mutagen X compounds, halonitromethanes, and cyanogen bromide pose potential concern, especially when desalinated waters are blended with native water having high disinfection by-product precursors present. Elevated concentrations of bromide can lead to the production of brominated DBPs when chlorine (Krasner et al. 1996) or ozone (Haag and Hoigne 1983) is used as a disinfectant. Brominated and iodinated DBPs have also been detected in the permeate of desalination facilities and its blends, and is a subject of much research (Richardson et al. 2003).

DISTRIBUTION SYSTEMS AND INTERNAL CORROSION CONTROL

Overview of the Causes of Internal Corrosion

Corrosive water generally produces elevated levels of copper and lead at the tap. Studies indicate that the highest levels of copper and lead occur in the first draw tap samples from single-family residential structures with interior plumbing of lead soldered copper pipes installed after 1982 (USEPA, 1991). Factors affecting the concentrations of lead and copper in the samples include the standing time of the water in the pipes, the type of solder used for the joints, and the quality of the plumbing installation. Other minor constituents imparted to the water are zinc and manganese which are present in most consumer interior plumbing systems.

The primary means of regulating copper and lead is by eliminating the electrochemical potential connection between the metal surface and water column. While it is true that the USEPA requires solder to be lead free (less than 0.17 percent Pb), most system corrections involve disrupting the electrical connection.

Internal corrosion of the distribution system piping deteriorates the quality of the potable water. Typically, this results in rusty water conditions, low chlorine residuals, bacterial regrowth, and an increase in copper and lead concentrations. Severe corrosion can cause tubercle formation, significant loss of hydraulic capacity, and eventually, pipe failure. Internal corrosion, in a distribution system with different types of pipe materials, is site specific. The primary interrelated factors that affect internal corrosion are:

- Flow velocity
- Workmanship and flux corrosion
- Galvanic corrosion
- Microbially induced corrosion
- Chemical factors (water quality)
- Stray current
- Temperature

Water quality characteristics in the distribution system are a function of the raw water supply and the processes that are used for treatment. Major water quality factors affecting internal corrosion include pH, conductivity, total dissolved solids, hardness, alkalinity, dissolved oxygen, chlorine residual, sulfate and chloride.

According to USEPA, corrosion causes the deterioration of crystalline structures that form the pipe materials, and can occur by one of three principle mechanisms:

1. Dissolution
2. Abrasion
3. Metabolic activity

Dissolution is a thermodynamic process where the solution is driven to equilibrium resulting from concentration gradients. Dissolved oxygen, pH, alkalinity, calcium, suspended solids, organic matter, buffer intensity, total salt concentration, chloride, sulfate, phosphate and silicate have shown to have different effects on the corrosion of different metals. The dissolution or corrosion of pipe materials occurs when water chemistry and physical conditions generate the following corrosion mechanisms.

- Uniform corrosion—when the water freely dissolves metal from the pipe surface.
- Concentration cell corrosion—when anodic and cathodic points are established along the pipe surface, causing the sacrifice of metals at the anode (dissolved metal species) and the precipitation of less soluble metal compounds at the cathode.
- Galvanic corrosion—when two dissimilar metals are in contact with each other, causing the dissolution of the anode.
- Dezincification corrosion—occurring in a copper-zinc alloy, such as brass, is the result of zinc being more anodic than copper and being corroded in water, leaving the copper in situ. Yellow brass is subject to severe dezincification in soft, non-stabilized waters; however, red brass and Admiralty brass metal containing less zinc are not subject to this type of corrosion.

Some of the primary constituents in the water that promote and support pitting attack are dissolved carbon dioxide and dissolved oxygen (Cohen and Meyers, 1987). Oxygen is usually present when corrosion occurs, and carbon dioxide is present at low pH values. Unlike generalized corrosion, pitting is associated with hard waters having high carbon dioxide and dissolved oxygen content, and most often occurs in cold-water copper piping in the horizontal runs of piping. Pitting has also been associated with stray current and impingement attack by high water velocities of copper. However, pitting attack is most common in new installations, with 80 to 90 percent of the reported failures occurring in the first 2 to 3 years, after which incidence of pitting is reduced (Schock, 1990).

Abrasion is the physical removal of pipe material due to irregularities in the pipe surface, which may dislodge under high fluid velocities. Abrasion of piping materials is typically accelerated when corrosion by-products, such as tubercles, are present in the distribution system. Abrasion activity normally diminishes when tubercles are reduced or if the tubercles can be coated with a less permeable substance. This effect has been noted by several full-scale systems, which have reported fewer customer complaints about red or black water events after corrosion control treatment was implemented (USEPA, 1992). There is a difference in the chemistry of corrosion control between flowing and standing conditions. This variation was evidenced by fluctuations in pH and increases in alkalinity for standing water compared with flowing water (Johnson, et al., 1994).

Metabolic activity is the utilization of pipe materials as a nutrient supply by microorganisms. Implementing corrosion control will alter the finished water chemistry, which subsequently may influence microbial growths within the distribution system. Recent studies have shown that biofilms are strongly associated with corrosion by-products within distribution systems. This association makes the biofilms more resistant to disinfection, and therefore, more persistent when active corrosion takes place in distribution system piping.

While biofilm formation may be promoted by corrosion, it remains difficult to accurately quantify the effects of microbial activity and the effect of treatment on such activity. Some potable water systems have experienced increases in distribution system microbial growth when corrosion control treatment was implemented due to the addition of nutrients to the finished water. In particular, this may become a problem within distribution systems where chloramines are used for final disinfection and a phosphorous-based inhibitor is applied for corrosion control.

As chloramines are reduced during oxidation, ammonia is released into the water. Thus the presence of two major nutrients, nitrogen and phosphorous, could increase microbial growth. This is especially likely in the extremes of the distribution system where localized areas with inadequate disinfection may occur (USEPA, 1992).

Certain qualities of RO permeate water can destroy certain types of piping materials, such as galvanized steel or asbestos-cement materials. Material selection for RO permeate is dependent on many design and site specific criteria, such as water type. For examples, the use of piping materials constructed of polyvinylchloride (PVC) may be selected for use in NF and brackish RO permeate, and whereas 304L stainless could be selected for fresh water, 316L stainless should be considered for brackish water. Other possible options include the use of duplex stainless for brackish water and specific alloys (for example 6% Moly) for seawater applications. Table A.1 summarizes a list of pipe materials and comments regarding corrosion. The chemical composition of permeate water produced by RO or NF when blended with other source water can cause water quality and infrastructure problems when distributed.

Indices for Predicting Corrosive and Scale Tendencies of Water

Several indices have been developed to indicate the stability or corrosivity of potable water. Although no single index is definitive, and some may at times be misleading, potable water corrosiveness or scaling potential can be evaluated and determined with a combination of indices. Each index provides information on the nature of the potable water; however, many of the indexes found in the water treatment and corrosion control literature are only approximations.

Corrosion Indices

For the purposes of this evaluation, buffer intensity, the calcium saturation index (CSI), Langelier saturation index (LSI), calcium carbonate precipitation potential (CCPP), Casil Index, Larson Ratio, and Ryzner index are typically considered, and are described as follows:

- *Buffer intensity.* This index measures the ability of the potable water to resist changes in pH that are caused by the addition of acids and bases. The index is expressed as milliequivalents or moles per liter of strong acid or base to change the pH by one unit. An index greater than 0.5 milliequivalents per pH unit is desirable. Water with low buffer intensity is frequently more corrosive. Wide variations in pH throughout the distribution system are reflective of water with low buffer intensity. Bicarbonate and carbonates provide the buffering capacity as measured by the alkalinity of the water.

Table A.1
Pipe material and corrosion

Pipe material	Comment
Copper	Corrosion of galvanized pipes; corrosion of household plumbing systems; erosion of natural deposits; leaching from wood preservatives. In drinking water containing minerals and dissolved oxygen, corrosion rates are from 5 to 25 µm/yr. In high purity water (very soft) protective films do not form on the internal copper surfaces and corrosion rates from 3 to 130 µm/yr occur, increasing with increasing oxygen and carbon dioxide content. Low sulfide concentrations (as low as 10 ppb) can accelerate corrosion of copper alloys.
Lead	Corrosion of household plumbing system;residue from man-made pollution such as auto emissions and paint; lead pipe, casing and solder. Waters of alkalinity of 60 mg/L or below will generally be less corrosive to lead if the pH is 7.5 or above. Increased dissolved oxygen will generally be expected to cause increased corrosion of lead.
Cast iron pipe	Interior corrosion, formation of tubercles, most biofilm growth, used for service lines. Internal corrosion will depend on water hardness, alkalinity, chlorides, sulfates, silica, dissolved gases, pH, temperature and velocity. Graphitic corrosion and bacterial attack are common causes of fracture of cast iron water piping; graphite dispersed in cast iron serves as the cathode, and the iron-silicon alloy, the anode. This results in the dissolution of the iron alloy and leaves black soft graphite as a structurally deficient material.
Lead pipe joints	Water is naturally corrosive and can pick up microscopic amounts of lead if it sits idle for extended periods of time.
Ductile iron pipe	Arsenic, mercury, and Bacillus subtilis all strongly adhere to cement-lined ductile iron pipe. Ductile iron pipe is typically furnished with cement-mortar lining to prevent internal corrosion.
Steel pipe	Used for service lines and taps; external corrosion can occur. Since pitting can be facilitated by the deposition of copper on zinc, galvanized steel should not be installed downstream of copper tubes and fittings. Stainless steel has good corrosion resistance to potable waters including soft (desalinated) supplies.
Plastic pipe	Used for water supply piping, resistant to corrosion ; lower tendency for biofilm growth than metallic counterparts. Many varieties available; brittleness can be a problem. Leaching of chemical plasticizer residuals can occur internally.
Asbestos cement	Asbestos-cement (AC) pipe has been widely used for potable water piping. Low pH, low alkalinity water are aggressive to AC pipes. Rates of deterioration can be reduced by chemical treatment to increase the water's buffer capacity but will not prevent the release of fibers from pipes that have already been degraded.

- *Langelier saturation index (LSI).* This index predicts whether a thin film of calcium carbonate is being formed on the walls. If the LSI is greater than zero, the water is considered to be scale forming, that is supersaturated with calcium carbonate. Waters with a LSI greater than zero are considered to be non-corrosive. If the LSI is less than zero, then the water is under saturated with calcium carbonate and the water will potentially dissolve calcium carbonate scales and would be considered to be corrosive. That is, a protective film of calcium carbonate will begin to dissolve into the potable water. The formula for the LSI is base on a comparison of the measured pH of a specific water (pH_a) with the pH that the water would have (pH_s) if at saturation with calcium carbonate (calcite) given the same calcium hardness and alkalinity for pH cases. Pisigan and Singley (1984) reported that the LSI is not a reliable indicator of the corrosive tendencies of potable water and that empirically chloride, sulfate, alkalinity, dissolved oxygen, buffer capacity, calcium, LSI and length of time of exposure provide more reliable information. The basic formula for the LSI is:

$$LSI = pH_a - pH_s \tag{A.30}$$

- *Calcium carbonate precipitation potential (CCPP).* This index is a refinement of the CSI and takes into consideration the capacity of the potable water to precipitate or dissolve calcium carbonate. The CCPP is a function of the calcium carbonate saturation. Reducing the pH and alkalinity increases the corrosion potential of the water. As noted in Lahav and Birnhack (2007), the calcium carbonate precipitation potential is a quantitative measure of the precise potential of a solution to precipitate or dissolve $CaCO_3$. It constitutes a parameter that can be used in the context of guidelines or regulations without invoking misunderstand. In contrast to the Langelier index which at times can be misguided. The CCPP, in contrast to the Langelier index, is easily understood in the context of guidelines and regulations. The precipitation of a thin layer of protective calcium carbonate (presumably calcite) was the earliest proposed method for controlling iron corrosion. However, few articles ever demonstrated a beneficial role of calcite in controlling corrosion as stated by McNeill and Edwards (2001). Systems that use CCPP or LSI, and should use both, as LSI can indicate the tendency to scale and CCCP can indicate how much scale will develop.
- *Calcium saturation index (CSI).* This index is a function of the calcium carbonate saturation. Reducing the bicarbonate concentration and pH will decrease the CSI. Declining CSI indicates a more corrosive water or calcium carbonate under saturation.
- *Casil index.* This index is based on a cation/anion balance. With a decrease of cations, the index is smaller and indicates more corrosive conditions. A decrease in the pH can increase the concentration of anions and may result in a lower index. The impact of desalinated water on the occurrence of nitrification in the distribution system will be added to the survey parameters.
- *Larson's ratio.* This index is calculated form the relative ratio of the total of chloride and sulfate ions to the total alkalinity of the water. Reactive anions form strong acid in anodic pits that form in the exposed corroding metal. Bicarbonate and other weak acids can precipitate a protective film on the exposed metal pipe wall. Index values greater than 0.4 indicate more corrosive water; a value less than 0.2 indicate a non-corrosive water.
- *Ryznar index.* This index is similar to the LSI, and is calculated as $RI = (2pH_s) - pH$ (Ryznar 1944). The Ryznar index yields values below 6.0 if scaling tendency is indicated, and a tendency to dissolve calcium carbonate is indicated at values above 6.0. This index provides a reasonably good estimate of expected scale formation even in the presence of phosphate-based inhibitors.

Corrosion Indices and Boron

Delion, Mauguin and Corsin (2004) modeled the corrosivity of Mediterranean seawater using software models, with 5.5 mg/l of total boron found in feed water samples of RO test conditions using a TFC spiral-wound membrane configuration, a fouling factor of 0.85, net feed pressure at 65 bar and a recovery of 40%. It was indicated that the Leroy ratio and Larson ratio should be used to model the corrosive potential of water (Delion et al. 2004).

- Leroy Ratio: (TAC)/(TH)
- Larson Ratio: $([Cl^-] + 2 \text{ X } [SO_4^{2-}])/([HCO_3^-])$

For low amounts of corrosion, Larson's Ratio should be less than 1 and Leroy's Ratio should be between 0.7–1.3. For post-treatment, Delion focuses on three parameters, concentrations of chlorides, sodium and boron. Along with these three parameters, the mineralization, temperature and recovery must be specific; otherwise results may vary. Utilizing a membrane with a higher rejection level will aid in reducing the amount of boron in the water. Reducing recovery, increasing feed pressure and increasing pH also aid in removal.

Corrosion Control Strategies and Stabilization

General Approaches

Corrosion control strategies can be divided into two general approaches. The difference between these two approaches is the mechanism by which a protective film is formed. The first approach includes precipitate formation of protective coatings for corrosion control. Water chemistry is adjusted to cause the precipitation of a compound onto the pipe wall and form the protective film. The success of this approach depends on the ability to form this precipitant and the characteristics of the deposits that result on the pipe walls.

The second approach involves the interaction of the potable water supply and the pipe material to form metal compounds that create a protective film of insoluble material for corrosion control. Passivation is the mechanism of this second approach. Adherence of the insoluble metal compound on the pipe wall determines the success of this approach. The primary options for corrosion control, particularly with respect to the LCR, includes (USEPA 2003):

- pH adjustment
- Bicarbonate stabilization (alkalinity adjustment)
- Calcium adjustment
- Inhibitor addition

In practice, there are a few typical methods employed for corrosion control treatment of desalted permeate. The corrosion control treatment strategies are evaluated in the following paragraphs.

pH Adjustment. Adjustment of pH is used to induce the formation of insoluble compounds on the exposed pipe walls. Passivation is the operating mechanisms for this corrosion control strategy. pH adjustment is accomplished with the addition of chemicals, such as lime, soda ash, sodium hydroxide, potassium hydroxide and carbon dioxide. pH adjustment is most suitable for source waters with low to moderate hardness and alkalinity levels (between 80 and 150 mg/L as $CaCO_3$). Frequently, this treatment technique is used in lieu of calcium carbonate precipitation. Some concerns with pH adjustment include higher trihalomethane formation potentials at pH values greater than 8.1, increased formation of other disinfection by-products at pH levels above 7.8, decreasing chloramines disinfection efficiency with pHs below 7.8, and a higher potential for calcium carbonate scaling in the distribution system pipe at pHs above 7.9.

Alkalinity Adjustment and Recovery. Alkalinity adjustment frequently is used to induce the formation of insoluble compounds on the pipe walls of the distribution system. Passivation is the operating mechanism for this corrosion control strategy. Carbonate passivation is achieved by incorporation of pipe materials into a metal hydroxide/carbonate protective film. This corrosion control strategy is most suitable for source waters with minimum alkalinity, and is frequently used in lieu of calcium carbonate precipitation. Alkalinity adjustment alters the concentration of dissolved inorganic carbonate (DIC) in the source water.

Alkalinity adjustment can be accomplished with lime, soda ash, sodium bicarbonate, sodium hydroxide, potassium hydroxide and carbon dioxide; sodium bicarbonate addition is preferable for alkalinity adjustment. Sodium hydroxide contributes little alkalinity to water, but can cause dramatic increases in pH. The primary disadvantages of alkalinity adjustment include:

- Capital, and operation and maintenance cost
- Increased carbonate scaling on the pipe walls

The primary benefit of alkalinity adjustment is increasing the buffering capacity for the source water. This helps to prevent wide fluctuations in pH throughout the distribution system. A buffer intensity greater than 0.5 milliequivalents per pH unit is indicative of a balanced, stabilized source water. The regional water appears to have adequate alkalinity and buffer intensity as long as the alkalinity is maintained at or above 100 mg/L as $CaCO_3$.

For groundwater treatment using RO and NF, the membrane can be considered as a closed system and the carbon dioxide will remain under pressure until exposed to an open system. Consequently, if acid addition is used for scaling control, the alkalinity in the raw water will be destroyed but not lost. Alkalinity recovery needs to be considered when selecting scaling control options, and depends on how much carbon dioxide and bicarbonate is in the raw water.

Normally, finished waters with 1 to 3 meq/L of bicarbonate alkalinity are considered highly desirable for corrosion control. Since carbon dioxide will pass unhindered through the membrane the desired amount of alkalinity can be recovered in the permeate by acidifying the desired amount, passing it through the membrane and adding the desired amount of base to convert the carbon dioxide back to its original bicarbonate form, and the reactions that describe these chemical processes are provided below.

Carbon dioxide that is converted from bicarbonate ion during pretreatment or post-treatment will be available in a closed system. Consequently the desired carbonate alkalinity in the finished water can be attained by carbon dioxide conversion before aeration, given presence of adequate CO_2. Normally, 1 to 3 meq/L of bicarbonate alkalinity is considered desirable for corrosion control. Since CO_2 passes unhindered through a membrane, the desired amount of alkalinity can be recovered in the permeate by acidifying the desired amount of bicarbonate ion, passing it through the membrane, and adding the desired amount of base to convert the carbon dioxide back to its original bicarbonate form. The reactions are shown below.

$$\begin{aligned} &HCO_3^- + H^+ \Rightarrow H_2CO_3 \\ &H_2CO_3 + OH^- \Rightarrow HCO_3^- + H_2O \end{aligned} \tag{A.31}$$

Aeration and Stabilization. If calcium and bicarbonate are present, the pH following aeration is controlled by $CaCO_3$ buffering and can be estimated by assuming $CaCO_3$ equilibrium.

$$pH_s = pK_2 + pK_{sp} + pCa + pHCO_3^- \tag{A.32}$$

The basic parameters that define the stabilization pH can be used to predict at what pH permeate should be conditioned to satisfy carbonate stabilization.

Calcium Carbonate Adjustment. The mechanism for this corrosion control strategy is the adjustment of the equilibrium for the calcium carbonate system for the source water. The objective for this treatment technique is the precipitation of a protective film of calcium carbonate onto the pipe walls. Calcium addition or removal is not necessary for the precipitation of calcium carbonate, rather this is accomplished with pH and alkalinity adjustment of the source water. The key to this treatment technique is to provide the conditions necessary for achieving calcium carbonate saturation.

Adjustment of the pH/alkalinity is done to create conditions necessary for the calcium and carbonate ions to exceed their solubility limits in water. Alkalinity or pH adjustment can be done with lime, soda ash, sodium bicarbonate or carbon dioxide. These chemical additives directly contribute calcium or carbonate ions to the water.

The concerns with using calcium carbonate adjustment include:

- Precipitating a uniform protective film throughout the distribution system,
- Reduction in the hydraulic capacity of the water lines, and
- Scaling in mechanical systems, such as boilers and hot water heaters.

Scaling is of particular concern for those water systems with high levels of non-carbonate hardness and sulfate. Adjustment of the pH is necessary for the precipitation of calcium carbonate and iron stability. For lower alkalinity waters, sulfate can also precipitate calcium and cause scale.

Use of Corrosion Inhibitors. Inhibitors have found wide spread use as a method of corrosion control. The most prominent forms of inhibitors used are polyphosphates, zinc phosphates, and silicates (AwwaRF and DVGW-Forschungsstelle 1985). Operating data indicate that the choice of inhibitor depends upon pH, alkalinity, calcium and total hardness, chloride, sulfide, iron concentrations, and dissolved oxygen levels of the source water. The inhibitors control corrosion by several mechanisms, including:

- Sequestering of the corrosion by-products, specifically lead and copper
- Scale inhibition
- Development of a coating film on the pipe walls
- Buffering the water at the desired pH

The mechanisms by which ortho-phosphates protect the surface are unclear. Unlike some corrosion scales that create a form of physical barrier to mass transport, phosphate films appear to passivate the corroding surface by changing the fundamental nature of the anodic reaction (Reiber, 1989). The copper-phosphate protective films are ineffective in low pH waters. Exposure to pH values < 6.0 degrades the film, destroying its protective qualities within a matter of hours (Reiber, 1989). Polyphosphates revert (hydrolyze) with time resulting in an increase in the ortho-phosphate ion (USEPA, 1992). This slow reversion of the polyphosphate to the ortho-phosphate form can allow the film formation to travel further into the distribution system (Harms, et al., 1994). The ortho-phosphate concentration must be maintained for the passivation to be effective as a corrosion control technique (Harms, et al., 1994).

However, addition of phosphates to the drinking water could ultimately aggravate operations and increase wastewater treatment costs. Zinc in wastewater can be a problem for receiving wastewater plants and may affect land application rates for biosolids derived from those plants (Ramaley, 1993). For public water systems that apply a phosphate-based corrosion inhibitor, USEPA mandates measurement of ortho-phosphate. USEPA's rational for this requirement is the lack of evidence supporting the ability of polyphosphates to control lead corrosion (USEPA, 1991).

Stabilization of Desalted Permeate

The need to stabilize water so that it would not enhance metal corrosion and concrete dissociation has been recognized for decades. In order to prevent corrosion the in the distribution system, the water purveyor distributing the water for blending with other water sources will have to include post-treatment in order to stabilize the water. Permeate from RO and NF processes are specific to the plant and usually pilot studies should be done before blending waters in order to determine the parameters in permeate and the needed adjustment to stabilize the water, so that, for example, "red water" does not occur.

As noted by Fritzmann et al(2007), untreated permeate from sea or brackish water RO plants does not conform to the drinking water standards such as WHO or the GDWQS. Due to the low TDS values RO permeate water can be unpalatable, corrosive, and un-healthy. Permeate must be re-hardened in order to prevent corrosion of pipes in the distribution network, pH value and carbon dioxide content need to be adjusted for scaling prevention and permeate water needs further disinfection.

Re-carbonation refers to process used to introduce bicarbonate and carbonate alkalinity to produce a positive LSI to prevent corrosion in pipes. Re-mineralization is a means of increasing the mineral content by addition to those which increase the bicarbonate or carbonate alkalinity of the desalinated water as stated by Withers (2005). Three main groups of post-treatment processes currently exist for stabilizing RO effluents:

1. Processes based on dosage of chemicals such as $Ca(OH)_2$ followed by CO_2;
2. Processes that are based on mixing the desalinated water with other water sources, with or without further adjustment of water quality parameter; and
3. Processes that center around dissolving $CaCO_3$ for alkalinity and Ca^{2+} supply followed by pH and CCPP adjustment using NaOH (Lahav and Birnhack 2007).

As stated by Lahav and Birnhack (2007), the first two groups are less commonly practiced because a) direct dosage of chemicals is usually expensive and b) desalinated water is diluted with other water sources further chemical dosage is usually unavoidable. The third process is the more cost effective of the two, particularly where $CaCO_3$ is available per Lahav and Birnhack (2007).

The above processes are explained accordingly by Withers (2005) including others processed that will aid post-treatment. Re-carbonation processes are explained by Withers (2005) as a method to add alkalinity to water to make it non-aggressive and or non-corrosive. It is the breakdown of lime by carbon dioxide as shown below:

$$2CO_2 + Ca(OH)_2 \rightarrow Ca(HCO_3)_2 \tag{A.33}$$

According to Fritzmann (2007), the most widely used method for re-mineralization if the dissolution of limestone by carbon dioxide according to the following reaction.

$$CO_2 + CaCO_3 + H_2O \rightarrow Ca(HCO_3)_2 \tag{A.34}$$

This method will produce water with a pH equal to pH_s. This method is mainly used because of the economic benefits in using limestone instead of lime and is cheaper overall.

Another method used is blending of desalination water with treated saline water source. As noted by Withers (2005), only partial stabilization can be achieved by blending the desalinated water with mineral rich waters such as brackish groundwaters or seawaters. This can help to improve the organoleptic quality of the water. This option is generally undertaken only for distillates from thermal distillation facilities.

In as study done by Al Arrayedhy (1987) post-treatment of RO permeates is stabilized using the following reaction:

$$NaOH + CO_2 \rightarrow Na^+ + HCO_3^- \tag{A.35}$$

These reactions were investigated by Al Arrayedhy (1987) that showed residual carbon dioxide may require further adjustment in the neutralization step of the RO process. Also alkalinity levels in the three processes shows neutralization with calcium carbonate and lime is better that neutralization with caustic soda.

Ruggieri and coworkers developed limestone selection criteria for EDR water remineralization (Ruggieri et al. 2008). Five commercially available limestones were characterized by mineralogical, chemical, and surface methods, including scanning electron microscopy (SEM). The main criteria in selecting a limestone for EDR water remineralization are its compositional purity in terms of both mineralogy and chemistry, and its textural characteristics. The dominant mineral phase in the uncontacted limestones was calcite ($CaCO_3$), and included small amounts of dolomite ($CaMg(CO_3)_2$) and quartz (SiO_2) and trace levels of clay matter. In relation to mineralogical purity, it was recommended that the occurrence other than calcite should be avoided, and that the use of SEM was a useful tool in evaluating surface texture influence on suspended particulate matter generation upon consumption of the bed (calcite).

Inhibitors

Inhibitors are especially formulated chemicals that are characterized by their ability to form metal complexes which reduce the potential for corrosion. The treatment mechanism is passivation of the metal pipe surface. Inhibitors commonly form inorganic scales with the pipe material. The scale acts as a diffusion barrier to both reactants and products of the corrosion half reactions. The electrical potential increases at the interface between the scale and the pipe wall.

Inhibitors are generally used to prevent scaling and corrosion in the distribution system. By adding various inhibitors to the source, such as polyphosphates, accounted for control of corrosion. Phosphate inhibitors have been added to drinking water since the early 1900s. Phosphates were first used to prevent excessive calcite precipitation. Researchers found that phosphates could sometimes prevent iron corrosion and red water problems (McNeill and Edwards 2001). Factors that determine the effectiveness of a particular inhibitor include:

- Initial water quality
- Type and dose of inhibitor
- Pipe material and condition

The corrosion rate of iron and copper depends on several factors, such as workmanship, flow velocity, etc., among others. Specific water quality factors include: pH, dissolved oxygen content, calcium saturation index, carbon dioxide levels and temperature. The relative ratio of chlorides, sulfates and bicarbonates also appear to influence the corrosion rate of pipe materials.

There are a diverse range of corrosion inhibitor formulations that are offered commercially by manufacturers/vendors. The two major types are phosphates and silicates. Inhibitors for use in potable water must comply with the standards established by the American National Standards Institute (ANSI) and NSF International, formerly the National Sanitation Foundation (NSF), Health Effect Standard 60 for Direct Additives to Drinking Water Supplies. The common types of inhibitors available include:

- Blended phosphates
- Orthophosphates
- Polyphosphates
- Pyrophosphates
- Metaphosphates
- Zinc phosphates
- Silicates

The type of inhibitor that may be used for corrosion control is determined by the calcium, alkalinity, pH and temperature of the source water. Other constituents that may affect the selection of an inhibitor and the effective dose include iron, manganese, total hardness, sulfate, chloride, sodium and TDS. The use of inhibitors for corrosion control is analogous to the maintenance of chlorine residual within the distribution system. The elevated initial dose is reduced after the distribution system becomes stabilized. A typical maintenance dose is 0.5 to 1.25 mg/L. Consideration should be given to the secondary impacts of using an inhibitor, particularly if the product is a pollutant of concern or interferes with reuse of treated effluent from the wastewater treatment facility.

The optimal pH range and the maximum dose are shown for typical inhibitors in Table A.2. Each type is discussed in the following sections. Inhibitors are effective over a constrained pH range. It is important to maintain the pH range throughout the distribution system as well as to utilize an inhibitor that is not subject to rapid hydrolysis effects. This requires that the source water be well buffered to the targeted pH range to prevent variations in the distribution system. Fluctuations in pH result primarily from low carbonate alkalinity.

Table A.2
Operating constraints of typical corrosion inhibitors

Type	pH Range	Maximum Dose, mg/L
Phosphates		
Orthophosphates	6.0 to 7.8	
Dipotassium		18–36
Disodium		14.3
Monopotassium		14.9
Monosodium		12.6
Tripotassium		22.4
Trisodium		17–41.5
Tricalcium		120
Zinc		20–50
Phosphoric Acid		12–14
Polyphosphates	7.6 to 8.0	
Polyphosphoric Acid		8.9
Potassium Tripolyphosphate		15.7
Sodium Glassy Polyphosphate		10
Sodium Tripolyphosphate		10–12.9
Pyrophosphates	7.5 to 8.3	
Sodium Acid		11.7
Tetrapotassium		16.6–29
Tetrasodium		10–14
Metaphosphates	7.0 to 9.0	
Sodium Hexa-metaphosphate		12
Sodium Tri- metaphosphate		10.7
Silicates	7.0 to 8.0	
Sodium		25
Potassium		25

Source: NSF. *Drinking Water Treatment Chemicals—Health Effects Standard 60* 2005.

Phosphate Inhibitors

To improve effectiveness, the distribution system often requires pretreatment with an elevated concentration of inhibitor followed by a continuous feed at a lower pre-determined dose. Initially, the addition of phosphates may remove scale and tubercles from the pipes. Phosphate inhibitor is particularly effective when the phosphate becomes a part of the metal precipitate or scale formation on the pipe surface. However, the amount needed is typically system specific.

Operating parameters to be considered in the evaluation of phosphate inhibitors are: (1) maintenance of a stable pH throughout the distribution system; (2) inhibitor composition for the specific water quality objectives and conditions; and (3) determining the appropriate dosage. Phosphate inhibitors are acidic solutions and can affect the pH of the source water. Since the formation of the phosphate precipitate is pH dependent, this parameter has the most significant impact on the effectiveness of the inhibitor.

Phosphate inhibitors are available in a variety of compositions, including sodium orthophosphate, zinc orthophosphate, polyphosphates and ortho/polyphosphate blends. Each formulation has a different percentage of effective orthophosphate (PO_4). Choice of a specific inhibitor requires consideration of the secondary impacts on wastewater treatment facilities, including the quality of the sludge and the effluent or reclaimed water for reuse. Orthophosphates appear to be the most effective inhibitor for a wide range of pipe materials. Copper solubility may not be reduced significantly by orthophosphates in solution. High doses generally are required for sequestering or passivation of copper in the source water. However, orthophosphates reduce the corrosion rates of iron, lead and galvanized steel. Orthophosphate precipitates metals at pH values above 7.8, which can cause a scale build-up within the distribution system pipes. Ortho-polyphosphates were developed to provide the benefits of both polyphosphates and orthophosphates in the treatment facilities and in the distribution system.

Polyphosphates, upon addition to water, hydrolyze with time to form orthophosphate ions. The rate of hydrolysis depends on pH and metal ions (such as calcium and zinc) present in potable water (Schock 1990). Monitoring of lead levels should be conducted to verify that the addition of polyphosphate inhibitors does not increase the solubility of this metal. Polyphosphates are typically used to sequester dissolved metals or cationic constituents, such as calcium, iron or manganese. This reduces their ability to precipitate in the distribution system.

According to McNeill and Edwards (2001), Polyphosphates were the first phosphates compounds used in corrosion control. Numerous studies have found that polyphosphates could prevent corrosion and/or control red water. The theory of polyphosphate corrosion prevention varies widely. Some researchers claim that polyphosphates adsorbed onto the iron surface to from a protective layer, where other studies have stressed the importance of calcium in polyphosphates effectiveness. In theory, polyphosphates may significantly increase the solubility of lead in domestic plumbing systems yet formulations containing more orthophosphate would be advantageous for use in potable water applications (Holm and Schock 1991). The effectiveness of polyphosphate decreases dramatically as the pH of the water increases above 7.0. This is due to the transition from a thick electro-deposited protective scale to a lighter adsorbed scale. Polyphosphates have been used to minimize the encrustation of filter media by post-precipitation of calcium carbonate. Polyphosphates can also effectively reduce the aesthetic coloration from Fe and Mn.

Blended phosphates consist of a mixture of both orthophosphate and polyphosphates. The mixture combines the corrosion inhibiting properties of the orthophosphate ion with the sequestering ability of the polyphosphates. Orthophosphate is an anodic inhibitor that suppresses the release and flow of electrons. Polyphosphates form a protective film on the pipe walls and inhibit the cathodic reaction. Metal phosphate complexes must achieve sufficient thickness to significantly reduce the rate of corrosion. Blended phosphates do not prevent metal corrosion, but they reduce the rate of corrosion to a manageable level.

Zinc orthophosphates are particularly effective for inhibition of iron and galvanized steel corrosion, especially at higher pHs. The typical dose is 1 to 2 mg/L. Pretreatment is required for initial scale formation. The presence of zinc reduces the dosage of phosphate for corrosion protection and increases the rate of inorganic scale formation on the pipe interior surface. Although little documentation exists in the literature to suggest that zinc phosphate inhibitors are effective for corrosion control, a recent study performed on 48 large and medium operating WTPs did show that zinc orthophosphate addition reduced 90th percentile lead concentrations at the consumer's tap

(Becker et.al. 1993). However, limitations in wastewater treatment or solubility limitations of basic zinc carbonate might provide limits on the use of zinc phosphate inhibitor formulations (Schock 1990). The concerns with using phosphate inhibitors include:

- Acceleration of bacterial re-growth potential in the distribution system
- Decreased effectiveness with stagnant water conditions in dead-ends of service lines
- Secondary impacts on wastewater treatment facilities, particularly effluent discharge standards and zinc concentrations in the bio-solids.

In the 1960s, manufactures began blending polyphosphates and orthophosphates with 5–25% zinc to for bimetallic phosphates, claiming either that the presence of zinc accelerated polyphosphate film formation or the zinc orthophosphate or zinc polyphosphate film was superior to regular phosphate films for inhibiting corrosion. These compounds reported a decrease in the corrosion compared to regular polyphosphates. However several studies found no benefit of zinc phosphates compared with regular phosphates (McNeill and Edwards 2001).

Silicate Inhibitors

Silicate inhibitors are prepared from the fusion of high quality silica sands to sodium or potassium salts. Sodium silicates are the most common form for this type of inhibitor. Sodium carbonate serves as the bonding salt which, due to the alkalinity added, raises the pH of the water. The typical ratio of silicate to sodium carbonate is a molar ratio of between 1.5 and 4 to 1. The typical inhibitor solution has 37 to 38 percent solids and a 3.22 weight ratio. Other formulations are available.

The effectiveness and the mechanism by which silicates inhibit corrosion of the internal surfaces of pipes are perhaps the least understood of inhibitor processes, even though silicates have been used regularly for corrosion control since the 1920s (Thompson et al. 2003). The mechanism for corrosion control using silicate inhibitors appears to be a combination of absorption and the formation of insoluble metal silicate compounds. Silicate inhibitors are considered to be anodic. Research indicates a slightly corroded surface may be necessary to form the protective silicate film. X-ray examination of pipe walls indicates the presence of a two layer protective film on cast or ductile iron pipes. The film is composed of an amorphous silicate layer that is adhered to an underlying silicate/metal surface.

Drinking water utilities have used silicates for decades. Initially, silicates were used for red water complaints in the distribution system. Also, silicates were used for zinc and aluminum corrosion control. Silicates have been found to reduce red and black water complaints resulting from the oxidation of naturally occurring iron and manganese in groundwater.

Silicate inhibitors are more effective than their phosphate counterparts in suppressing crevice or pitting corrosion. This is due to the alkalinity provided by the bonding salt. A dissolved oxygen concentration above 0.25 mg/L is necessary for silicate inhibitors to form a film on oxidized metal surfaces. Silicate inhibitors significantly reduce the corrosion of A/C pipe. The silicates combine with the pipe material to form a quartz-like protective film.

Historically, silicate inhibitors have received mixed opinions due in part to the mystery surrounding its functionality and the wide variety of different experimental results. Silicate compounds were originally used as a coagulation aid. Early studies found that natural silica present in water was concentrated in the relatively protective iron scale. Addition of silicate based inhibitors has also been found to reduce iron corrosion rate and raise the pH, which is generally beneficial toward iron corrosion.

In a study by LaRosa-Thompson et al. (1997), X-ray photoelectron spectroscopy (XPS) analysis showed that a silicate film forms on the interior of the pipes. This film helps inhibit corrosion as indicated by the studies in which silicates were compared to sodium hydroxide of the same pH. Silicate provided more corrosion control than NaOH. Other experiments had a negative influence on the effectiveness of silicate. The following consequences of silicates use include:

- Difficulty in controlling the rate of deposition of silicate-based film on the pipe walls
- Release of corrosion by-products into the potable water
- Protective films cannot be re-dissolved
- Continuous treatment is necessary
- Effectiveness is reduced by low flow velocities and higher pH levels
- Metal ions can exert a high demand for the inhibitor
- Glassification of mechanical equipment
- Ability to confirm copper corrosion control for source water with high calcium content.

Successful attempts of mitigating lead release with silicate have been documented as early as the 1920s (Thresh 1922). Despite its history of application, there have been few studies documenting quantitative relationships between silicate and metal (lead) release. Of the few studies, there remains a general uncertainty surrounding the nature by which Si effects lead release. Early studies were carried out by Lehrman and Shuldener (1951) that assessed the possible mechanism of silica film formations in distribution systems.

Relatively recent studies have had mixed implications on the effectiveness and role of silicate for corrosion control. Generally, silicate addition has been documented within the literature as beneficial (Schock and Wagner 1985; Johnson et al. 1993; Lytle et al. 1996; Pinto et al. 1997; Chiodini 1998; Schock et al. 2005). However, the association between silicate dose and pH has proven to present difficulties when comparing with a control. In some cases, the pH of the control will remain unadjusted, implying that the difference between the control and Si treated experimental unit will consist of an effect from pH and silica. The beneficial effect of pH increase for lead control has been well documented (Schock 1989). Because of the increase in pH associated with Si addition, some researchers have suggested that the effect of Si is essentially equivalent to pH adjustment (Ryder and Wagner 1985).

BLENDING CONSIDERATIONS AND AGRICULTURAL ISSUES

The process of generating fresh water from brackish or salt water using a RO process yields permeate that is low in pH and alkalinity. If the pH and alkalinity of this water is not adjusted, it may create a corrosion problem in the existing water distribution system. These problems include but are not limited to issues with the taste and odor of the water, discoloration of the water (turbidity), and corrosion of distribution components.

Often desalted permeate is stabilized by blending a small portion of the source water into the (permeate) product water, the purpose of which, is to help in stabilizing the product water thereby reducing water corrosivity. Blending permeate with raw groundwater is the least cost remineralization technique and is accomplished simply by routing a portion of the raw groundwater around the desalting process and blending it with permeate. However, the amount of alkalinity and hardness that can be added is often times limited by other parameters such as chlorides and the disinfection byproduct precursors non-purgeable dissolved organic carbon (NPDOC) and bromide.

Adding or blending pre-treated source water into the product water (permeate) can help in stabilizing the product water thereby reducing the impact of the before mentioned issues but introduces the need for disinfection of the pre-treated water prior to or after blending. Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies (Lovins et al. 2004b; Duranceau and Lovins 2005). This subject is of great importance for many water purveyors. Blending of variable and differing water supplies where desalted water serves as one of the supplies is become more frequent.

Blend Water Ratios

Blending ratios can be calculated by use of a mass balance equation (Bergman & Elarde 2005). When blending waters from multiple sources, it is helpful to use a multi-objective technique to evaluate the optimum blend for a particular distribution system requirement. Water blended to produce an alkalinity level to reduce the corrosion of iron components could result in a negative impact with regards to the increased corrosion of copper components. Blending to produce a high level of sulfates in the product water will lead to an increase in the corrosion of iron components but decrease corrosion of copper components. These conflicting attributes indicate that the utility maintaining the distribution system will need to identify the necessary mixture for their particular system (Imran et.al. 2006).

Furthermore, blending of permeate with native waters for post-treatment purposes could be limited by the amount of iron and manganese concentrations present in the native water, as these constituents can cause taste and odor, stains, and hence would limit overall blend ratios. In addition, if the native water used as a source of blend water consists of natural organic matter, which could impact disinfection by-product formation in the blended water. This is significant if bromide of appreciable amounts (on the order of 0.5 mg/L) is present in the post-treated permeate, where disinfection is required. Blended water may also contain unwanted pathogens (Bergman & Elarde 2005). When integrating into an existing system, control over disinfectants and fluorination chemicals should be optimized for maximum efficiency (Duranceau 2006).

Impacts on Existing Distribution System Infrastructure

As water is transported through a distribution system, physical, chemical and/or microbiological transformations may occur, resulting in degraded water quality. Aged water distribution systems typically have achieved some state of quasi-equilibrium and have as a result minimal problems. However, changes in water quality and conditions can affect water distribution systems significantly, particularly if new water supplies or different water supplies are used to supplement water resources for the community. This is often the case when existing groundwater supplies are converted to a mixture of surface water and desalted source waters. These interactions occur in the bulk water phase and surfaces in contact with the water column.

Blended Water Compatibility

Water to be used for blending must be analyzed to determine that they are chemically compatible and that the total dissolved solids, color, and DBP formation potential will not adversely affect the water quality (Bergman & Elarde 2005). When blending water from multiple sources a blending facility will be required to reduce variations in water quality (Duranceau 2006). The important of predicting the possible chemical mixture of the product water is of great importance, therefore a number of mixing methods can be employed (Trussell and Thomas 1971).

Tampa Bay Water and Water Research Foundation (formerly AwwaRF) commissioned a study on corrosion problems in water distribution systems that have historically relied on groundwaters that are now being required to obtain water from other sources. A pilot plant was constructed using pipes from the existing distribution system. These pipes consisted of polyvinyl chloride (PVC), unlined iron, lined iron, and galvanized iron pipes. The pilot plant blended water from three sources; groundwater (GW), surface water (SW), and desalted water (RO). This plant was operated for 2 years and detailed sampling was taken of the various water blends and piping combinations.

Collected data was used to create a mathematical model that would be used to calculate the corrosiveness of different water blends. Mathematical models were developed for corrosiveness predictions for several metals of concern: iron, lead, copper. For example, one model was investigated as a general corrosive model, with input variables for the corrosiveness model were pH, alkalinity, calcium, magnesium, sodium, chloride, sulfates, UV_{254}, iron, turbidity, dissolved oxygen, apparent color, chlorine, and conductivity, as follows:

$$\Delta C = \frac{[10^{\beta 0}(DO)^{\beta 1}(Cond)^{\beta 2}(SO_4^{2-})^{\beta 3}(Cl^-)^{\beta 4}(Na)^{\beta 5}(T)^{\beta 6}(HRT)^{\beta 7}]}{[(Alk)^{\beta 8}(Ca^{2+})^{\beta 9}(SiO_2)^{\beta 10}(UV)^{\beta 11}(pH)^{\beta 12}]} \tag{A.36}$$

Iron was released from both unlined cast iron pipe and galvanized steel when the finished water alkalinity was less than the groundwater alkalinity in the blend. The iron was predominantly to be found in the particulate form, which could result in high color. Minor color release was also observed in blends that contained increased levels of sulfates (from treated surface water) or chlorides (from desalted permeate). There was found to be no significant color release from PVC or lined cast iron pipe. The input variables for the development of an iron release model were temperature, alkalinity, chloride, sodium, sulfate, dissolved oxygen, and HRT. The mathematical formula was:

$$\Delta C = \frac{[(DO)^{0.967}(SO_4^{2-})^{0.118}(Cl^-)^{0.485}(Na^+)^{0.561}(T)^{0.813}(HRT)^{0.836}]}{[(Alk)^{0.91}(10)^{1.321}]} \tag{A.37}$$

Models were further created to predict the release of copper, the release of lead, the release of iron, and the dissipation of the secondary disinfectant monochloramine in the distribution system. The input variables for the copper release model were temperature, alkalinity, pH, sulfate, and SiO_2. The mathematical formula was determined to be:

$$Cu = (T)^{0.72}(Alk)^{0.73}(pH)^{-2.726}(SO_4^{2-})^{0.1}(SiO_2)^{-0.22} \tag{A.38}$$

The release of total copper was also described by steady-state water quality models and was found to exceed the copper action level when groundwater alone was utilized due to high carbonate alkalinity. The adverse effects of alkalinity on copper release had been historically been mitigated through the use of pH adjustment and corrosion control inhibitor addition. A positive aspect of blending surface water with mixtures of ground and desalted seawater was reduced copper corrosion. Lead historically had not been a challenge for the water system studied, but was a concern when the system was converted to a blended water of desalted seawater, iron-coagulated and filtered surface water, and groundwater. Similarly, input variables for the lead release model were temperature, alkalinity, pH, sulfate, and chloride. The mathematical formula was best modeled as:

$$Pb = (1.027)^{(T-25)}(Alk)^{0.677}(pH)^{-2.86}(SO_4^{2-})^{-0.228}(Cl)^{1.462} \tag{A.39}$$

Based on these findings, TBW has maintained finished water alkalinity of 100 mg/L as $CaCO_3$, or more, which offsets the majority of released color from unlined iron piping components. Also, blends of water that contained more than 60 percent groundwater created unacceptably high releases of copper to the distribution system, while blends of less than 20 percent increase corrosion due to low water alkalinity. Blends with desalted water allowed this ratio to increase.

It was also determined that blends with high ratios of desalted and surface waters should be avoided as they result in corrosive blends. Limitations on the amount of groundwater available for blending may require the use of inhibitors in the blend. These results were for low flow conditions. High flow distribution systems would be required to calibrate the models in order to compensate for velocity gradient conditions. Dissipation of chlorine residuals was found to be dependent on pipe material, geometry, hydraulics (residence time and velocity), and water quality (organic carbon). Combined chlorine dissipated more rapidly than did free chlorine in reactions with the pipe wall for unlined cast iron and galvanized steel pipes, and less rapidly in reactions with the bulk water. These results indicated that maintenance of any residual in a summertime conditions (30°C) will not be possible for hydraulic conditions that exceed 48hrs in galvanized steel and difficult in unlined cast iron pipe. Also, it was shown that free chlorine was found to maintain 100 times (2 log) less HPC growth than chloramines.

The transition effects for total iron, copper, and lead (that is, changing of water quality from one blend or source to another) were predictable using steady-state models developed for iron, copper and lead release and coupled with time-release models. Total iron, copper and lead transition following blending would produce predictable effects that would stabilize in 30 to 40 days. The results indicated that potential adverse of blending could be mitigated if anticipated.

Blending can hence improve the stability of the product water by increasing the alkalinity and calcium in the permeate and reduce the corrosiveness of the water (Hendricks 2006; Binnie, Kimber, and Smethurst 2002). The water that is to be used for blending may be the source water used for the RO process or from another source (Bergman and Elarde 2005). When integrating into an existing system, control over corrosion inhibitors and pH adjustment should be optimized for maximum efficiency (Duranceau 2006). It is necessary to model the affects of different blends to prevent the release of red water in the distribution system (Imran, Dietz, Mutoti, Taylor, Randell and Cooper 2005).

Unfortunately, blending will not stabilize the product water completely. The membrane permeate will still need to have calcium infused into it for partial stability. This can be accomplished by employing either lime or limestone treatment. If the source of the water to be blended with the product water from the RO system is from a ground source from a limestone or chalk geological formation, the amount of lime treatment will be substantially reduced (Withers 2005).

Blending will reduce the stress on the membrane system as it reduces the amount of water that needs to be treated and thereby reduce the operating costs of the system (Bergman and Elarde 2005). The utility will need to develop a unidirectional flushing program for the RO system. The utility will need to increase storage reservoir size and maintenance. The utility should expect to see an increase in its operational and maintenance expenses (Duranceau 2006).

Red Water Experiences

Red water is a phenomenon that describes a situation where a layer of iron oxides is detached from the internal surface of metal pipes into water (Lahav and Birnhack 2007). Post-treatment to meet drinking and irrigation water standards is therefore an essential part of most RO plants according to Fritzmann, Lowenberg, Wintgens, and Merlin (2007).

The most problematic phenomenon in urban distribution systems is related to the release of dissolved metals to the water (Lahav and Birnhack 2007). Desalinated water has been pumped directly into the distribution system without being mixed with other water sources in the system. The permeate water is then blended with the water sources in the pipe and will cause problems in the system. The most problematic occurrence is the phenomenon of “red water” which describes a situation where a layer of mostly iron oxides is detached from the internal surface of metal pipes into the water and arrives at the consumer’s tap with a characteristic yellow-brown-red color (Lahav and Birnhack 2007).

Corrosion of iron pipes according to McNeill and Edwards (2001) in a distribution system can cause three distinct related problems. (1) Pipe mass is lost through oxidation to soluble iron species or iron bearing scale. (2) The scale can accumulate to large tubercles that increase head loss and decrease water capacity. (3) The release of soluble or particulate iron corrosion by products to the water decreases the aesthetic quality and lead to consumer complaints of “red water” at the tap.

Selection of post-treatment processes may not completely consider the impacts on the distribution system, particularly when blending multiple varying supplies (Lovins et al. 2004b; Duranceau and Lovins 2005). Only recently has this subject become of importance for many water purveyors. Blending of variable and differing water supplies where desalted water serves as one of the supplies is becoming increasingly more frequent.

A considerable number of studies exist that describe the potential problems that may occur when waters that have different chemical characteristics are supplied intermittently into distribution systems as stated by Imran et al. (2005). The most problematic occurrence is the phenomenon of “red water” which describes a situation where a layer of (mostly) iron oxides is detached from the internal surface of metal pipes into the water and arrives at the consumer’s tap with a characteristic yellow-brown-red color. In this regard Tang et al. (2006) state appropriately that adverse impacts of blending different source waters on iron release have not yet been investigated systematically.

Nevertheless, large occurrences of the red water phenomenon, such as the one reported in 1993 by Price in the city of Tuscon, Arizona, due to an abrupt change in the water source affected the confidence that the public had in the local water authorities, especially if the public becomes aware of a possible connection between the problem and the introduction of a new water source (e.g., desalinated water). Another well known problem is the deterioration of metal pipes due to slow corrosion. Beyond destroying the pipes, the products of corrosion consume chlorine products rendering disinfection less efficient, it creates scales on the pipe's surface that increase the energy required for pumping, it supports biofilm growth and may produce suspensions of (mainly) iron particles that result in water that are not appealing to the consumer per Sarin and others (2004) .

To date, no formal unifying regulations exists worldwide that define unequivocally the quality of desalinated water that should be released to a distribution system. In most places the desalinated water is simply expected to conform to the general water quality requirements. Specific issues such as quality problems that may arise from the in-line blending of desalinated water with groundwater or the lack of certain minerals in the water when it is used for drinking and/or agricultural irrigation are to-date being thoroughly addressed for the first time per the World Health Organization and Yermiyahu (2006, 2007). The need to stabilize the water so that it would not enhance metal corrosion and concrete dissolution has been recognized for decades.

The most problematic phenomenon in urban distribution systems is associated with the release of dissolved metal ions to the water (mostly iron ions but also Zn^{2+} from galvanized pipes and Pb^{2+} and Cu^{2+} ions from certain fittings, invariably installed in water distribution systems). In Israel the problem is typically restricted to small diameter (<3") pipes in the urban and household systems (pipes with greater diameters are typically protected by cement coating). Since the most stable thermodynamic state of iron is Fe(III), elemental iron solid tends to donate electrons and transform into Fe(II) and Fe(III), with dissolved oxygen and chlorine species being the most common electron acceptors in the distribution system. This unavoidable phenomenon causes the formation of a layer on the internal surface area of the pipe, which is typically referred to as a "corrosion scale."

Depending on specific conditions, the reactions may result in a continuous dissolution of metal ions into the water, or may give rise to precipitation of minerals on the active electrochemical sites on the pipe's internal surface. The latter occurrence may cause the formation of a "passivation layer," which, depending on its properties (width, density, species composition), can serve, on the one hand, as a protection layer which reduces the diffusion of dissolved oxygen and ions to the surface of the pipe and thus reduces the rate of corrosion and disintegration of the pipe, but on the other hand, its sudden collapse/dissolution may cause the release of a relatively large amount of iron (and other) species into the water which may cause the known phenomenon of "red water" to occur (Taylor et al. 2005).

With regard to establishing an effective passivation layer, the chemical stability of drinking water is commonly described by three parameters: (1) the buffering capacity of the water, i.e., the ability of the water to withstand substantial changes in pH when a strong base or a strong acid are added to it, which is a function of the alkalinity and pH values; (2) the propensity of the water to precipitate $CaCO_3$, which can be controlled by a variety of qualitative (e.g., Langelier Saturation Index) and quantitative (e.g., the Calcium Carbonate Precipitation Potential, CCPP) indices; and (3) the soluble Ca^{2+} concentration in the water. The fourth relevant parameter, pH, is a dependant parameter that is determined by the values of the previous three. However, pH is the easiest parameter to measure and control, and thus, combined with alkalinity and $[Ca^{2+}]$ are the parameters used to assess and control water stability, typically via the CCPP.

Corrosion inhibitors are also used to decline the corrosives of CF/RO treated water. Per the AWWA (2007), phosphate and silicate inhibitors can form protective films on pipe walls that limit corrosion or reduce metal solubility. Orthophosphates react with pipe metal ions, which build a passivation layer. And silicate inhibitors can form a glasslike file on pipe walls. These inhibitors should be added a few weeks to allow these protective films to form.

Permeate and Agriculture

Desalted Seawater Supplies and Permeate Boron Concentrations

Boron is naturally occurring in the environment, the majority of which occurs in the ocean, a result of the natural weathering of landmass sedimentary rocks (Magara et al. 1998), its presence in silts, or introduction because of detergents or soap usage (Bick and Oron 2005). Seawater contains between 4 and 6 mg/L of boron, and up to 7 mg/L in the Arabian Gulf, the amount of which depends on global location and season. Boron typically exists as non-ionic boric acid [$B(OH)_3$] in natural seawater having a pH range between 7.7 and 8.3 pH units, since boron has a pK_a of 9.3 at 20 degrees Celcius (Rodriguez et al. 2001):

$$B(OH)_3 + OH^- = B(OH)_4^- \qquad pK_a = 9.3 \tag{A.40}$$

In 1993 the WHO issued a drinking water boron guideline value of 0.3 mg/L (WHO 2004), whereas, the Japanese Water Quality Standard for boron remained 1.0 mg/L (Melnik et.al. 1999). This value was amended to 0.5 mg/L in 1998, and may be further revised to an increased value between 1 and 2 mg/L in the near term, based on criteria established for human health concerns because boron is suspected to cause birth defects at high concentrations. The lower standard levels have been historically associated with agricultural concerns, as boron at elevated levels may be harmful to crops when desalinated seawater is used for irrigation purposes. Although trace quantities of boron are essential for plant growth, higher levels of crop boron exposure can cause foliage damage, premature ripening of fruits and in some cases toxic to citrus and other tree species at elevated levels (Bush et al. 2003). For example, although most citrus species have a boron tolerance of only 0.4 to 0.75 mg/L, vegetables can withstand boron exposures as high as 4 mg/L (Bick and Oron 2005).

Since seawater RO membranes remove only 40 to 60 percent of non-ionic boron from the feedwater, depending on membrane type, age, pretreatment pH and temperature (Pervov et al. 2003), permeate water boron values can range between 1.0 and 2.0 mg/L (Prats et.al. 2003), which is higher than current WHO guidelines. Rejection of boron is significantly improved when the pH is higher, due to the boron existing as the ionized borate species [$B(OH)_4$]$^-$. Boron rejection will thus increase with degree of dissociation, rising for example from 80 percent to 99 percent at pH 9 and 11, respectively. Therefore, seawater desalination plants will typically employ additional methods of treatment to achieve this goal, which can include:

- The passage of permeate water through additional RO treatment trains (treatment pass);
- Adjustment of the permeated pH prior to further brackish water RO processing;
- Increasing the pH of the feed water for increased seawater boron rejection;
- Treatment of permeate with ion-exchange; or,
- Blending permeate with an alternative non-saline water sources.

Taniguchi et al. (2004) investigated two post-treatment processes relative to boron removal from water supplies: brackish water RO and adsorption. It was determined that whereas RO is not effective a lower operation pH, adsorption has been shown to be very effective. However, the adsorption process requires a large empty bed contact time and requires expensive medias. As a result, combined or hybrid process trains have been proposed as alternative treatment options.

Bonnelye et al. (2007) showed that boron exists primarily as boric acid a pH of approximately 8.2 in Curacao seawater, and investigated the use of a two-pass RO system for the control of boron in the permeate water. The second pass included the use of caustic soda addition for pH adjustment to transform boric acid to borate, which was shown to increase Boron rejection. Post-treatment included re-mineralization through limestone filters, UV disinfection and GAC filtration, and the process achieved a finished water boron level of 0.3 mg/L.

As a result, the additional requirements needed for increased boron removal will increase the cost of seawater desalination. The lower value for boron is an agriculture-related issue reflecting boron's herbicidal effect at values of 0.5 mg/L or higher for some crops. The difference in a treatment goal of 1 mg/L and 0.3 mg/L for boron could mean the difference between a single-pass RO process and a two-pass RO process, translating to a 15 or 20 percent increase in total present cost for the additional capital, operation and maintenance costs associated with additional treatment.

Desalination and the Sodium Adsorption Ratio

As the use of desalinated water supplies continues to grow, its use for irrigation will also continue to increase. For example, in Spain, approximately 22 percent of desalinated water is used for agricultural irrigation (Beltran and Koo-Oshima 2006). In light of several new Australian plants coming on-line, an Australian survey determined that 53 percent of the population is anticipating that desalinated water will be used for irrigation in the future (Dolnicar and Schafer 2006). In Israel, water desalinated from the Mediterranean Sea at the Ashkelon facility provides water for both municipal and irrigation purposes (Lahav and Birnhack 2007).

However, desalination removes ions that are essential to plant growth, and if used to replace irrigation water that previously provided basic nutrients like calcium, magnesium and sulfate at levels sufficient to limit the need for additional fertilization requirements. Calcium is important for proper plant growth, and changes in its content and relative concentrations can be problematic for agriculture (Yermiyahu et al. 2007). Moreover, sulfate is removed from the permeate during desalination. Sulfur deficiency could become a problem in other systems where alternative methods for calcium enrichment are practices. For horticultural purposes, the average recommended sulfate concentration in irrigation water ranges from 141 mg/L (as S) for tomatoes to 58 mg/L (as S) for non-vegetable crops. Other constituents that may create potential impacts on vegetation include salinity, suspended solids, biodegradable organics, pathogens, nutrients, stable organics, pH, heavy metals, dissolved organics, and residual chlorine.

The sodium adsorption ratio (SAR) is defined as being the concentration of sodium (Na) divided by the square root of the quantity equal to one half of the sum of the concentrations of calcium (Ca) and magnesium (Mg), where all concentrations are expressed in milliequivalents per liter, as shown in Equation A.41:

$$\text{SAR} = \frac{\text{Na}}{\sqrt{\frac{\text{Ca} + \text{Mg}}{2}}} \tag{A.41}$$

The SAR commonly is used in association with electrical conductivity (EC_w) of the irrigation water to evaluate potential hazards associated with sodium (Rowe and Abdel-Magid, 1995).

To some extent, the degree of concern for desalinated water use for irrigation is related to SAR and EC_w. The use of desalinated water will cause concern when the water has lower EC_w values, typically less than 200 for SAR values between 0 and 3 units (Rowe and Abdel-Magid 1995). On the other hand, for SAR levels of 20 or higher, severe restrictions may be imposed if the EC_w is less than 2,900 µmhos/cm. Hence the SAR and conductivity should be evaluated concurrently for this application of desalinated water. The effect of the SAR is that sodium will take the place of the calcium and magnesium present in the clay particles of the soil. This reaction reduces the effective infiltration capacity of the soil. The SAR is of great concern in areas with high clay content, however in areas with sandy soil containing little to no clay, the SAR concerns are less critical. The SAR is also of less concern when regular "leaching" occurs when water with little to no sodium content washes the soil profile. An example of this would be seasonal rains on an annual basis. Another concern with the SAR is the salinity, which is measured as conductivity. As the conductivity increases, the SAR's infiltration effects are not as critical, so that a range of 3 to 7 is provided for blending targets for desalinated permeate. Conductivity, sodium adsorption ratio, calcium, magnesium, potassium and sodium are the more critical parameters monitored for the proper management of turfgrass for golf course facilities.

Typical irrigation water quality goals for Bermuda turf grass are based on several parameters, and include conductivity, SAR, calcium, magnesium, potassium, sodium, iron, chloride, sulfate, boron, alkalinity and total dissolved solids (Rowe and Abdel-Magid, 1995). If the minerals required for agriculture are not added to the permeate water prior to irrigation, affected agricultural industries will need to supplement required nutrient loadings via the use of fertilization or blending with native sources, either of which may be cost prohibitive (fertilizers) or limited due to drought or climate change (native sources).

SUMMARY OF LITERATURE FINDINGS

Desalination will result in the production of water having low dissolved solids content that can and will cause internal corrosion, and may not be fit for human consumption. Pure water is considered a reactive chemical: when air is dissolved in extremely pure water, the resultant solution is very corrosive. Water that contains little to no hardness would be considered unhealthy for potable use and water that contains no dissolved oxygen may be offensive and taste flat. Consequently, post-treatment of membrane desalinated water is required prior to storage and distribution for municipal water purveyors, and must include disinfection.

There are four primary issues concerning the post-treatment water. These relate to blending, remineralization, disinfection and the materials used for storage and transport of the water to the tap. Desalinated water is often blended with other sources that contribute minerals to the final blended water. Seawater as a source for blending is limited due to issues related to corrosivity and taste if the blending levels exceed about 1%. Blending of permeate water with seawater results in the addition of sodium, potassium, calcium, and magnesium to drinking-water but also will contribute bromide and iodide which are DBP precursors, and is limited in quantity due to the significant concentrations of these constituents. Consideration should be given to the natural minerals present and whether these will result in finished water having unacceptable water qualities in addition to unacceptable taste and odor.

Membranes do not remove small, uncharged molecular contaminants or dissolved gases such as carbon dioxide, hydrogen sulfide and methane. If hydrogen sulfide is present in a source groundwater, it must be removed, typically by packed tower or air stripping processes prior to disinfection and distribution to consumers. If sulfides are removed in the stripping process, then provision are also made to remove (scrub) the off-gas sulfides from the air stripping tower off-gas to prevent odor and external corrosion issues on surrounding buildings and infrastructure. The stripping of carbon dioxide and hydrogen sulfide raises the pH and reduces the amount of base needed to perform stabilization. Permeate is typically low in calcium, magnesium, alkalinity and may have a low pH if acid was used for pretreatment ahead of the membrane process. Since the permeate is corrosive to downstream piping and appurtenances, alkalinity and pH adjustments are accomplished with bases such as sodium hydroxide, and inhibitors may also be employed for corrosion control purposes.

There is also an issue regarding potential anthropogenic pollutants from a range of sources which need to be considered on a local basis, whenever any external and potentially minimally treated source is used, taking into account potential pollution sources and threats. Disinfection and filtration of the blending water will be necessary if there is any possibility of microbiological or other regulated parameter contamination, in which case similar considerations regarding the formation of by-products in the blending water apply.

Generally the natural organic matter or TOC content in finished water is very low and the yield of by-products from final disinfection would be expected to be low as a consequence (McGuire Environmental 2004). However, blending with other source waters can prove to be problematic for desalted permeate, should bromide and iodide be present, or should the blend not provide enough buffering to the desalted permeate resulting in an unstable finished water.

Chemicals and Post-Treatment Issues

Post-treatment may be achieved by the addition of chemicals as described in the literature. If this is undertaken there are three primary concerns that need to be addressed:

1. The quality of the additives and the introduction of chemical contaminants produced during the manufacture, storage, distribution and transport. Unlike pre-treatment chemicals, there are no downstream processes that will remove undesirable contaminants.
2. Controlling dose rates so that required concentrations are provided.
3. Preventing or minimizing unwanted chemical reactions following chemical addition. This issue is similar to blending. Localized changes can occur at dosing points leading to fouling problems on a micro-scale.

Brackish and Seawater Post-Treatment

Post-treatment of the permeate water from the desalination processes can include several unit operations, each dependant upon the source water type and desalination method. Considerations of post-treatment, based on literature findings, will include:

- Stabilization by addition caustic hydroxide alkalinity is the most widely used approach for brackish desalinated permeate in order to provide corrosion control for metallic pipelines and distribution systems, although this method is often accompanied by the addition of corrosion control inhibitors. Stabilization can also be achieved by carbonate alkalinity adjustment, re-mineralization by blending with source water(s) and the use of caustic soda-carbon dioxide or calcite bed contactors have been reported.

- The enhanced removal of specific compounds (i.e., boron, silica, NDMA, etc.) is site specific and source dependant.
- Sodium hypochlorite and chlorine gas are most widely used for disinfection of desalinated water. However, the use of chloramines instead of chlorine for residual disinfection is more advantageous when product water must be conveyed over long distances (over 100 km), or when stored for long periods of time (several days) due to the significantly lower decay rate of chloramines compared to free chlorine.
- Use of ozone as a disinfectant for desalinated water is limited as this practice has the potential of forming bromate as a disinfection by-product.
- Blending of desalinated water for re-mineralization is suitable with brackish water, and only up to about 1% with seawater. The raw water used for blending should be pretreated for chemical and microbial control prior to mixing with the desalinated water.

The primary desalination water plant post-treatment unit operations for potable water supplies reliant upon brackish groundwater are the following (AWWA 2007; Duranceau, 1993):

a. Carbon dioxide removal (degasification or decarbonation);
b. Hydrogen sulfide removal (stripping) and odor control treatment (scrubbing);
c. Alkalinity recovery, pH adjustment, stabilization and corrosion control; and,
d. Disinfection.

Alternative treatments reported for use in seawater desalination post-treatment applications include (Withers 2005):

1. Addition of carbon dioxide and excess lime;
2. Filtration of carbon dioxide dosed permeate through limestone bed contactors;
3. Application of sodium carbonate and hydrated lime;
4. Application of sodium bicarbonate and calcium sulfate;
5. Application of sodium bicarbonate and calcium chloride;
6. Blending with a native low-salinity water source or by-pass blending.

Remineralization can be categorized into a series of four treatment processes: (1) chemical addition without lime or limestone; (2) carbon dioxide addition followed by limestone bed contactors for dolomitic dissolution, (3) carbonic acid addition followed by lime dosing; and (4) blending with water containing high mineral content.

APPENDIX B
POST-TREATMENT STABILIZATION OF DESALINATED WATER
POST-TREATMENT QUESTIONNAIRE

1. For questions that may require more space than is provided, please use a separate sheet of paper.
2. Handwritten responses are preferred to avoid transcription errors during typing.
3. Write NIA if no information is available.
4. Please return the completed questionnaire to:

Steven J. Duranceau, PhD, PE
Civil, Environmental and Construction Engineering
UNIVERSITY OF CENTRAL FLORIDA

Should you have any questions regarding this questionnaire, please contact Steven Duranceau.

I. BACKGROUND INFORMATION

Name and address of the membrane plant:

1. Plant Name: ____

2. Plant Address: ____
____
____

3. Plant Type: ____

a. Categorize by the TDS of Feed:
_______ Seawater [SW]: (20,000–35,000 mg/L TDS)
_______ High Brackish Groundwater [GW]: (>7,500–<20,000 mg/L TDS)
_______ High Brackish Surface Water [SFW]: (>7,500–<15,000 mg/L TDS)
_______ Low Brackish GW: (1,000–5,000 mg/L TDS)
_______ Low Brackish SFW: (1,000–2,500 mg/L TDS)
_______ Fresh GW: (<1,000 mg/L)
_______ Fresh SFW: (<1,000 mg/L)
_______ Others (please explain)

b. Is it GWUI (Groundwater under the influence of surface water)? ________________

4. Contact Person and Telephone Number:

Name: ______________________________

Telephone Number: ______________________________

Email Address: ______________________________

5. Web Site Address: ______________________________

6. Name of Owner ______________________________

Address of Owner: ______________________________

7 Public or Private Ownership:

_______ Public Agency (Municipality)
_______ Water Authority
_______ Private Agency
_______ Others (please describe)

8. Water Quality Driver (Check all that apply):

_______ Arsenic
_______ Salt Removal
_______ Hardness Removal
_______ TOC Removal
_______ Color Removal
_______ Radionuclide Removal
_______ SOC Removal
_______ Specific Contaminant
_______ (please specify) ______________________________
_______ Others (please specify) ______________________________

II. RO/NF MEMBRANE PLANT DESIGN CHARACTERISTICS

a. General Design Data

1. Plant Production Startup Date: __________ (mm/yyyy)

2. Design Hydraulic Capacity of Plant: __________ mgd or __________ million L/day

3. Plant Originally Designed for Expansion: __________ yes __________ no

4. Design Percent RO Feedwater Recovery: __________ percent (%)

5. Design RO Membrane Flux: __________ gal/day-ft^2 __________ L/hr-m^2

6. Design Pressure: __________ psi (max) __________ bar (max)

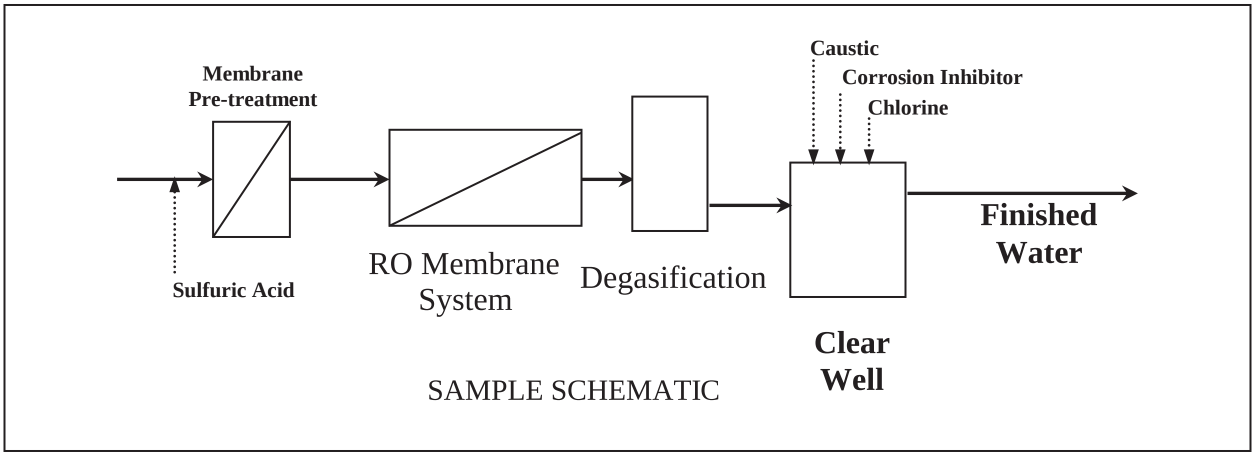
__________ psi (min) __________ bar (min)

7. What is the end use of the RO/NF permeate? (Check all that apply)

________ Potable Water
________ Industrial Use
________ Groundwater Recharge (for indirect potable reuse)
________ Groundwater Recharge (seawater intrusion barrier)
________ Irrigation
________ Others (please specify)

b. Plant Schematic

Please attach an overall schematic of the plant showing any pre- and post-treatment processes to membrane filtration, including location chemical addition. Acceptable file formats: GIF, JPG, PDF, MS Powerpoint, MS Word, MS Excel. Note that hardcopies, including handwritten hardcopies are acceptable and can be sent via regular mail.



c. Source Water

________ Ocean Intake
________ Ocean Well
________ Brackish Water Well
________ Fresh Groundwater Well
________ Gulf/Bay
________ Lake/Reservoir
________ Flowing Stream/River
________ Agricultural Drainage
________ Other (please specify) ______________________________________

III. POST-TREATMENT INFORMATION

Post-Treatment Information

1. Post-treatment type: (Check all that apply)
    - ________ Air stripping/desulfurization
    - ________ Degasification/decarbonation
    - ________ Caustic chemical addition
    - ________ Corrosion inhibitor addition
    - ________ Blending
        - ________ Treated surface water
        - ________ Treated groundwater
        - ________ Other (please specify)

2. Disinfection:

Primary ________ Chlorine
________ Ozone
________ UV
________ Chlorine dioxide
________ Other (please specify) ____

Secondary ________ Chlorine
________ Chloramine
________ Other (please specify) ____

3. Not taking into account the membrane process, what are your post-treatment disinfection and disinfectant residual goals?

____

____

____

____

4. Have you experienced any post-treatment problems within the plant? (Check all that apply)
    - ________ Blending limitation like salt concentration or DBP precursors
    - ________ Scaling of degasification/stripping towers
    - ________ Biogrowth in degasification/stripping towers
    - ________ Chemical injector plugging
    - ________ Specific issues with cleaning post-treatment equipment
    - ________ White water formation
    - ________ Corrosion events
    - ________ Colored or red water
    - ________ Others (please specify) ____

5. Any distribution system impacts noted? (Check all that apply)

________ Corrosion events (infrastructure)
________ Lead and Copper Rule impacts
________ Disinfection By-Products
________ Taste and odor
________ Detention time prior to point of entry to distribution system
________ Detention time after point of entry to distribution system
________ pH stability
________ Disinfection residual stability
________ White water
________ Color
________ Red water/black water
________ Biological regrowth
________ Others (please specify) ____

6. Provide blended or by-pass description (if applicable):

____

____

____

7. Are blending tanks/structures used? ________

8. What is your sequence of post-treatment operations?

____

____

____

9. How do you control the pH and buffering content of the post treated RO water prior to release into the system?

____

____

____

10. Describe your method of corrosion control. (Check all that apply)

________ pH Adjustment
________ Alkalinity adjustment
________ Hardness adjustment
________ Corrosion inhibitor, type: ____
________ Blending
________ Others (please describe) ____

IV. POST-TREATMENT WATER QUALITY

Please complete the following table. Enter the low, high, and average values, if known. If not, the average value is required. If data is not available for any particular parameter, enter “NA.” If an analytical result was below detection limit, enter “BDL.”

Water quality data									
	RO permeate			Blend water (if used)			Point of entry to distribution system (POE)		
Parameters	Low	High	Average	Low	High	Average	Low	High	Average
Temperature, °C									
pH [R]									
Alkalinity, mg/L as $CaCO_3$									
Turbidity, NTU									
Conductivity, µmho/cm									
Total Dissolved Solids, mg/L									
Total Organic Carbon, mg/L									
Color, CPU									
Total Suspended Solids, mg/L									

Water quality data (continued)

Parameters	RO permeate			Blend water (if used)			Point of entry to distribution system (POE)		
	Low	High	Average	Low	High	Average	Low	High	Average
Sodium, mg/L									
Potassium, mg/L									
Barium, mg/L									
Calcium, mg/L									
Magnesium, mg/L									
Strontium, mg/L									
Iron, mg/L									
Manganese, mg/L									
Silica, mg/L									
Sulfate, mg/L									
Chloride, mg/L									
Bromide, mg/L									
Phosphate, mg/L as PO_4									

Water quality data (continued)									
	RO permeate			Blend water (if used)			Point of entry to distribution system (POE)		
Parameters	Low	High	Average	Low	High	Average	Low	High	Average
Aluminum, mg/L									
Fluoride, mg/L									
Hydrogen Sulfide, mg/L									
Selenium, mg/L									
Microbiological Quality									
Total Coliform bacteria, #/100 mL									
Algal Counts, #/mL									
Heterotrophic plate count bacteria, cfu/mL									
Pseudomonas, #/100 mL									
Stability Index									
LSI									
Ryznar									

V. POST-TREATMENT OPERATION

	Average	Maximum (if available)	
1. Daily NF/RO permeate production:			mgd

2. Flow, mgd	Low	High	Average
Permeate			
Blend			

3. Post-treatment chemicals (include residual disinfectant, pH adjustment, corrosion inhibitor chemicals):

Chemicals	Average dose rates
______________________	______________________
______________________	______________________
______________________	______________________
______________________	______________________

4. Blend ratio, as a percentage (%) of total flow to plant. ______________________________

5. Control of blending operation:
Provide a brief description on how the plant controls post-treatment operations.

____

____

____

____

VI. POST-TREATMENT O&M COSTS

O&M in $/1000 gal

1. Overall operating post-treatment cost ______________ (specify US$ or Euro$)

2. Breakdown of O&M cost
    - Labor ______________ (specify US$ or Euro$)
    - Chemicals ______________ (specify US$ or Euro$)
    - Energy ______________ (specify US$ or Euro$)
    - Membrane replacement ______________ (specify US$ or Euro$)
    - Replacement parts (not membranes) ______________ (specify US$ or Euro$)
    - Concentrate disposal ______________ (specify US$ or Euro$)
    - Other (please specify) ______________ (specify US$ or Euro$

3. Current energy cost ______________ (specify US$/KWH or Euro$/KWH)

4. Other (please provide)

VII. LESSONS LEARNED

Please share with us lessons learned or major issues confronted after your desalting plant was placed into service (the following are provided as example topics).

1. Pilot Testing. Did pilot testing reveal any water quality concerns for distribution system?

    ____

    ____

2. Design. Did design of facility consider impacts of permeate on the distribution system?

    ____

    ____

    ____

3. Permitting/regulations. With respect to post-treatment (disinfection), what obstacles were overcome to obtain permits/consents?

    ____

    ____

    ____

4. Startup. Did you experience issues in distribution system after plant startup and if so, what did you do to resolve the problem?

____

____

____

5. Operations. Are these issues in distribution system that has been directly related back to post-treatment?

____

____

____

6. Other Additional Comments:

____

____

____

____

____

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____

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ABBREVIATIONS

a	radius
AWWA	American Water Works Association
AwwaRF	Awwa Research Foundation (now Water Research Foundation)
BAT	best available technology
c, C	concentration of species
$CaCO_3$	calcite
$CaMg(CO_3)_2$	dolomite
$CaSO_{4(s)}$	gypsum
CEB	chemically enhanced backwash
CFS	coagulation, flocculation, and sedimentation
CIP	clean-in-place
CTA	cellulose triacetate
CWA	Clean Water Act
d	diameter
D	diffusivity
DAF	dissolved air flotation
D_B	Brownian diffusivity
DBP	disinfection by-product
DBPFP	disinfection by-product formation potential
DBPFP	disinfection by-product formation precursor
DC	direct current
d_h	hydraulic diameter
DIC	dissolved inorganic carbon
DOC	dissolved organic carbon
δ	thickness
E	electrical potential
ED/EDR	electrodialysis/electrodialysis reversal
EDTA	ethylenediaminetetraacetic acid
ε	porosity
η	relative viscosity
G	free energy
GAC	granular activated carbon
GWDR	Groundwater Disinfection Rule
Γ	lag coefficient
F	force

HAA	haloacetic acid
HFF	hollow fine fiber
HPC	heterotrophic plate count
I	current; ionic strength
IDSE	initial distribution system evaluation
IMS	integrated membrane system
IOC	inorganic compound
J	flux
k	mass transfer coefficient
k_b	diffusion coefficient from surface to bulk
k_i	mass transfer coefficient of solute
kJ	kilojoule
kPa	kilopascal
K_{pf}	fitting constant
k_s	distribution coefficient
K_{s0}	solubility constant
k_w	mass transfer coefficient of solvent
K_w	specific hydraulic permeability
L	phenomenological coefficient
LCR	Lead and Copper Rule
LRV	log reduction value
LSI	Langelier saturation index
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
γ	activity coefficient
m^3/d	cubic meters per day
MF	microfiltration
MFI	modified fouling index
mgd	million gallons per day
MTC	mass transfer coefficient
MW	molecular weight
MWC	molecular weight cutoff
μ	absolute viscosity
NF	nanofiltration
NOM	natural organic matter
NPDES	National Pollutant Discharge Elimination System
ν	kinematic viscosity
ω	shear rate

p, P	pressure
PAA	polyacrylic acid
PAC	powder activated carbon
PDT	pressure decay test
PES	polyethersulfone
PF	polarization factor
psi	pounds per square inch
PV	pressure vessel
PVDF	polyvinylidene fluoride
Π	osmotic pressure
ψ	particle passage
Q	flow rate; reaction quotient
r	recovery
R	global rejection
Re	Reynolds number
R_E	electrical resistance
R_f	resistance of the filter
R_g	ideal gas constant
R_k	resistance of the cake
R_m	hydraulic resistance
RO	reverse osmosis
ρ	density
SDI	silt density index
SDWA	Safe Drinking Water Act
SEM	scanning electron microscopy
Sh	Sherwood number
SHMP	sodium hexametaphosphate
SiO_2	quartz
SOC	synthetic organic compound
SW	spiral wound
SWTR	Surface Water Treatment Rule
σ	reflection coefficient
T	temperature
t_+	cation transport number
TCF	temperature correction factor
TCR	Total Coliform Rule
TDS	total dissolved salts
TH	total hardness
THMFP	trihalomethane formation potential
TMP	transmembrane pressure drop
τ	shear stress

θ	temperature correction factor constant
u	velocity
UF	ultrafiltration
UIC	underground injection control
V	molar volume
VOC	volatile organic compound
WHO	World Health Organization
x, X	fraction of material
Z	modified mass transfer coefficient
$Z_{i,cp}$	modified film theory mass transfer coefficient
ξ	fouling potential

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