<u>MnTAP Industrial Chloride Reduction</u>

MnTAP Intern Project Report
Minneapolis, MN

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2021

Preface

The work described in this report is a service of the Minnesota Technical Assistance Program (MnTAP), University of Minnesota, School of Public Health, Division of Environmental Health Sciences. MnTAP is funded primarily by the Minnesota Pollution Control Agency's Prevention and Assistance division.

MnTAP helps Minnesota businesses implement industry-tailored solutions that maximize resource efficiency, increase energy efficiency, prevent pollution, and reduce costs to improve public health and the environment.

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Table of Contents

Background

Company Description

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Company Background

The Minnesota Pollution Control Agency (MPCA) is committed to ensuring every Minnesotan has healthy air, sustainable lands, clean water and a better climate. MPCA works with the Minnesota Technical Assistance Program (MnTAP), an outreach program in the School of Public Health at the University of Minnesota. This partnership provides pollution prevention technical assistance to businesses and organizations around the state to reduce pollution at its source to improve public health and the environment.

Incentives for Change

Chloride is toxic to aquatic life which is concerning given the widespread use of chloride salt in residential, commercial, and industrial settings. Even small amounts of chloride have the potential to pollute large amounts of water, with 1 teaspoon of salt enough to pollute 5 gallons of water. In 2020, there were 50 bodies of water in Minnesota listed as impaired due to chloride, 40 of these are in the seven-country Twin Cities Metropolitan Area. [1] It is important that chloride discharge is reduced to preserve the health of our aquatic environments. While there are treatment options available for removing chloride from wastewater effluent, these options are not economically feasible. Optimizing water softeners ensures that salt is used efficiently, thereby reducing the amount of chloride discharged.

Sources of Chloride Effluent

In 2020, Overbo et al. estimated the amount of chloride contribution from various source in Minnesota. The study showed that the greatest source of chloride contribution to the environment were road salt, fertilizers, and wastewater treatment plants (WWTPs). Road salt contributes 403,600 tons of chloride per season, Fertilizers contributes 221,300 tons of chloride per year and WWTPs contribute 209,900 tons of chloride per year. [2] The major chloride contributor to WWTPs were water softening operations, contributing almost 65%. Industrial chloride contribution, which includes industrial water softening operations, accounts for 21% of the chloride WWTPs receive. [2] From the above estimates, the softening operations lead to 136,400 tons of chloride per year in Minnesota, and this estimate is based solely on residential and commercial softening operations. [2]

Industrial chloride usage can be classified into three distinct categories: 1) Product Ingredients, 2) Process Aids and 3) Water Softening. Product Ingredients refers to substances that are a necessary ingredient in the final product, a good example would be some food or beverage products. It is hard to reduce the salt consumption if it is used as a Product Ingredient as this may have adverse effects on the quality of the final product. Process Aids refer to substances that are not directly used in the final product but are used in processes to perform a certain function, a good example would be using salt in brine chillers. Finally, Water Softening is when hard water is softened to make it usable in an industrial process. The next section describes how water softening operations use salt. This project was focused on identifying the opportunity to reduce chloride discharge by optimizing water softener use.

Current Technologies

<u>Ion Exchange Water Softening:</u>

Water is an essential ingredient in most industrial processes, and it serves numerous functions depending on the industry. However, a significant challenge with the raw incoming water is its hardness, the calcium and magnesium ion content in the water. Hard water causes a lot of problems in industrial processes from scaling deposits in piping, boilers, and cooling towers, to poor lathering and function of soaps. Scaling by hard water comes in two categories: 1) hard scale which is calcium carbonate in its calcite crystalline form and 2) soft scale which is calcium carbonate in its aragonite crystalline form. [3] Hard scale is usually the scaling that occurs when untreated hard water is used, soft scale on the other hand is more sludge-like deposition and can be easily cleaned but it still results in fouling if not cleaned.

Water hardness is measured using a scale of grains of $CaCO_3$ per gallon (gpg). 1 gpg translates to 17.1 parts per million of $CaCO_3$. [4] Water is considered "soft" at <1 gpg and "very hard" at >10 gpg, with typical water in southern Minnesota having a hardness of 15-25 gpg. The water hardness is calculated using Equation 1. [4]

$$2.5[Ca^{2+}] + 4.1[Mg^{2+}] = [CaCO_3] \qquad 1$$

To remove the hardness from water, a softener is commonly used which removes the calcium and magnesium ions from the incoming hard water and outputs soft water. Most water softeners use the principle of ion exchange. [5] Hard water containing calcium and magnesium ions passes through a resin bed, which is saturated with sodium ions. The heavier and more charged calcium and magnesium ions exchange with the sodium ions and cling to the resin. The output water has minimal concentrations of calcium and magnesium ions but contains higher concentrations of sodium ions and is called soft water. Eventually, the resin bed will saturate with calcium and magnesium ions and lose its ability to soften water. To regain its softening ability, brine (water saturated with NaCl or KCl) is used in a process called regeneration. [5] Due to the high concentration of sodium ions in the brine solution, the sodium ions exchange with the calcium and magnesium ions in the resin and re-saturate the resin bed. The calcium and magnesium ions along with the chloride ions and leftover sodium ions from the regenerating brine are then discharged as wastewater. [5] Figure 1 below highlights the process of ion exchange and regeneration.

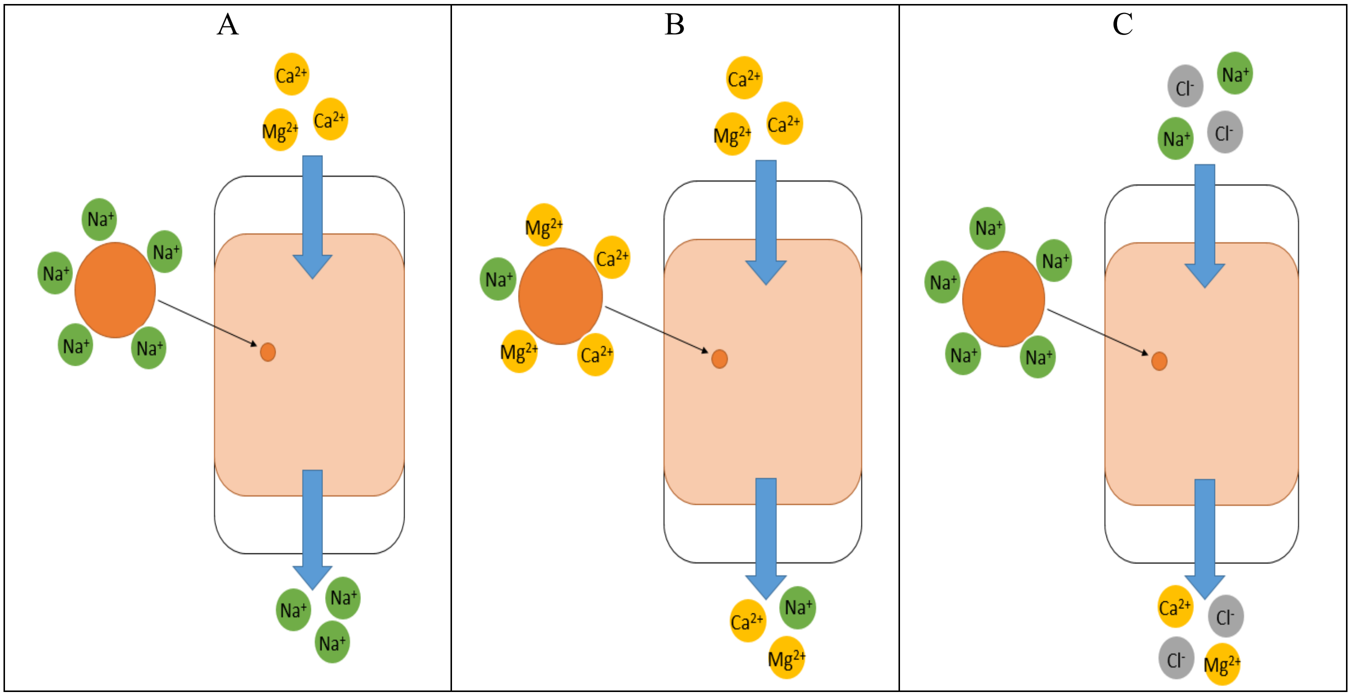


Figure 1: (A) Resin is charged with Na^+ ions and can remove the Ca^{2+} and Mg^{2+} ions and the output water have Na^+ ions. (B) This resin gets eventually saturated with Ca^{2+} and Mg^{2+} ions. (C) Regeneration occurs and re-saturates the resin using brine and the discharge contains Ca^{2+}, Mg^{2+} and Cl^- ions

Ion-exchange resin is made of organic polymer microbeads. Polystyrene Sulfonate is commonly used in the resin microbeads fabrication. [6] The negative charge on the sulfonate groups interacts with cations to hold them in place. Figure 2 shows the ion-exchange process with polystyrene sulfonate polymer resin.

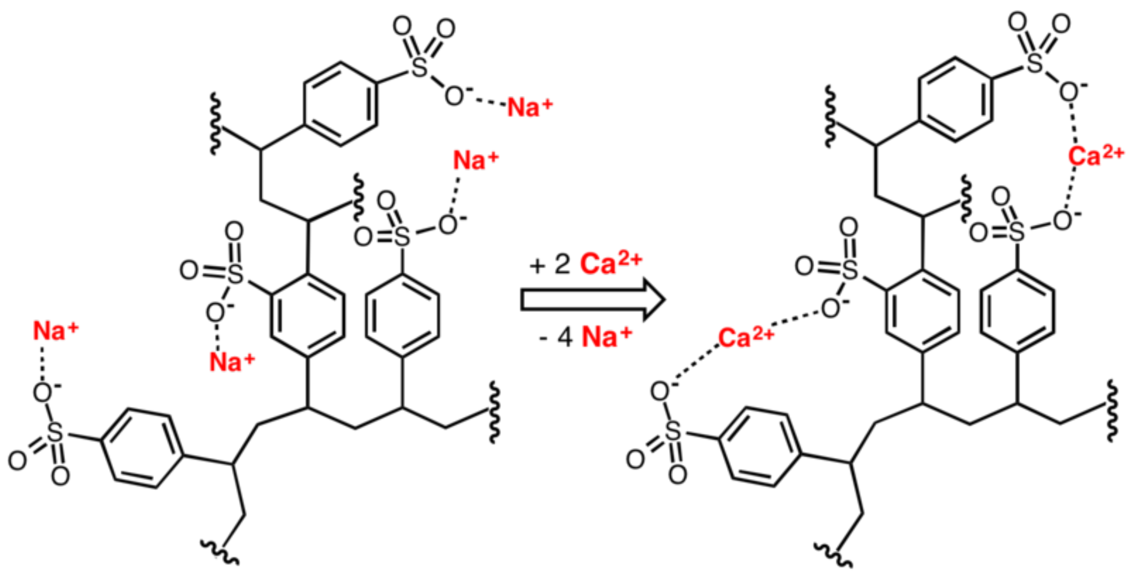


Figure 2: Polystyrene Sulfonate replacing Ca^{2+} ions with Na^+ ions, Ion-exchange process [7]

Water Softener Operations

All water softeners have three main components: 1) a resin bed, 2) a brine tank and 3) a control valve/control head. The resin bed resides within a tank where the ion exchange occurs, while the brine tank holds the salt that will be used for regeneration. The control valve is located on the resin tank and triggers the regeneration process at the appropriate time. Water softeners may have different methods of regeneration, different kinds of control valves, and the number and cycling of resin beds. Potassium chloride is also a suitable salt for the regeneration process but is required in higher quantities when compared to its sodium chloride counterpart. [8]

Regeneration

Most regenerations follow five phases chronologically: Backwash, Brine Rinse, Slow Rinse, Rapid Rinse and Brine Refill. [9] In the Backwash phase, water flows though the resin in the opposite direction causing the resin to expand in volume. [9] This step serves two purposes: 1) Fluff the resin to increase the regenerating efficiency of the resin and 2) Remove foulants and impurities stuck on the resin. [9] The length of this phase depends on if the raw incoming water has high concentrations of iron, manganese and other organic foulants. During the Brine Rinse stage, brine is drawn from the brine tank and then run through the resin bed. [9] This is the regeneration step which removes the calcium and magnesium ions in the resin and replaces it with sodium ions again. [9] The optimal regeneration brine concentration is 8-10 wt%. In the Slow Rinse phase, the ion exchange process continues while also rinsing out excess sodium chloride. The following stage is the Rapid Rinse phase where water is run through the resin at high flowrates to remove excess sodium chloride from the softener. [9] Finally, a Brine Refill stage occurs wherein water is added to the brine tank allowing it to saturate with salt for the next regeneration cycle. Sometimes, the Brine Refill stage is skipped if the softener has float valves which constantly keeps the water level above the salt. [9]

The regeneration process is triggered by two primary methods: Demand-Initiated Regeneration (DIR) and Time-Initiated Regeneration (TIR). A demand-initiated regeneration, as the name suggests, regenerates the resin based on demand i.e., it will monitor the water flow and then start the regeneration process after a certain volume of water. [10] On the other hand, time-initiated regeneration recharges the resin after a set amount of time. A DIR system ensures more efficient use of salt and water as there is no pre-mature regeneration and thereby reduces chloride discharge. [10]

Additionally, the regeneration process may be co-current or counter current. The more conventional method is co-current regeneration, where in the brine flows in the same direction as the water flows. Alternatively, in a counter-current regeneration system the regenerating brine flows in the opposite direction of the water. Counter-current regeneration is more efficient than the co-current regeneration systems, needing 35%-40% less salt and using 40% less water. [11]

Tank Configuration

Another softener variation is the number of resin beds and whether they soften water together or in an alternating fashion. Single softening systems and Twin/Multiple alternating softening systems are common. The main distinction between these two variations is that the former has only one resin bed while the latter has multiple resin beds. In the single tank system, when the regeneration process occurs, soft water becomes unavailable and therefore it becomes necessary to arrange the regeneration time for when soft water is not in high demand. However, in a twin or multiple tank alternating system, while one of the tanks regenerates, the other resin tank can soften water ensuring a continuous supply of soft water. A twin or multiple tank system also ensures that the resin beds face significantly less wear and tear when compared to its single counterpart. A twin or multiple tank softening system is also more efficient in terms of salt usage and water usage, using 15-30% less salt and water when it is compared to a single tank system. [11]

To handle high volumes of water a parallel tank system is used. This system has multiple resin beds that work concurrently instead of alternatively. These systems use salt and water more efficiently when compared to a single tank of the same volume. The resin also faces less degradation and wear and tear when compared to a single softener with a larger volume. [11] However, a parallel tank system occupies more space and requires additional plumbing work.

Best Management Practices – Softener Optimization Flowchart

A softener optimization flowchart (Appendix A) was created to guide industrial water softener users to optimization strategies for their specific softening system. The flowchart was created based on informational interviews with Jeff Hill at Robert. B. Hill Co. and Jay McNab at Culligan Co. and from BMPs observed by Madison Metropolitan Sewerage District (MMSD), the Water Quality Association (WQA), and Minnesota Pollution Control Agency (MPCA). The flowchart directs users to BMPs for their specific softener based on the responses to questions in the flowchart. The flowchart considers what processes use soft water, the water supply, the age of the softener and the resin, and the water softener settings.

The softener optimization flowchart uses yellow diamonds to represent yes-no questions which, depending on the answer, direct to a certain optimization. Orange squares represent recommendations or optimization strategies that can be performed on softening operations. A user will start at the head of the flowchart for each independent softener and work down the flowchart. The full flowchart is in Appendix A. Since the full flowchart is extensive, the flowchart was broken into the boxed sections below. The paragraphs below each correspond to a yellow diamond or an orange square giving further instruction and explanation.

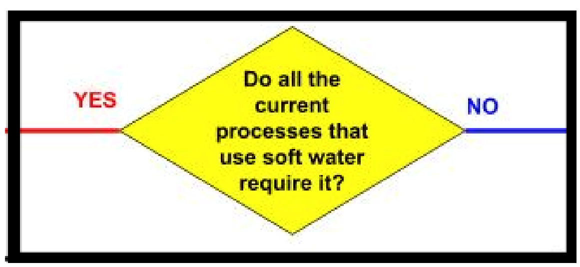


Figure 3: The first question box in the softener optimization flowchart.

Do all the current processes that use soft water require it?

It is important to identify all the processes that use soft water. This is the first step in the flowchart (see Figure 3). Doing this will help quantify how much water is softened and where the softened water goes after it leaves the softener. After identifying the various processes that use soft water, each process can be evaluated to check if it requires soft water. For example, irrigation does not require soft water. If a process does not require soft water, the best management practice is to bypass the water softener when supplying water to the process. Additionally, some processes may need completely soft water (< 1 gpg) while other processes just need water that is below a certain hardness threshold. If a process does require soft water but does not need water to have a hardness of 0-1 gpg, then it may be possible to use other water conditioning alternatives.

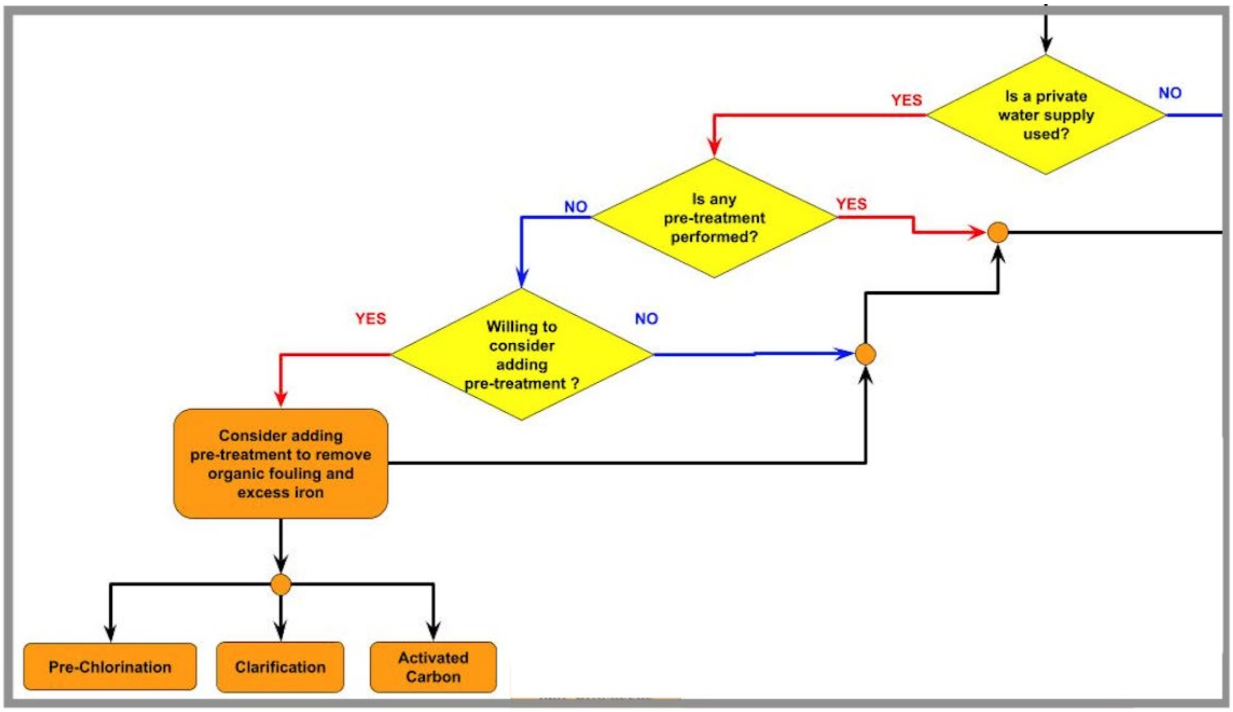


Figure 4: Softener optimization flowchart section showing the water supply considerations.

Is a private water supply used?

It is important to know whether the water supplied to the facility is provided by the municipality or by a private water supply (see Figure 4). This is important since it helps determine whether water pre-treatment is required before the water is softened. The presence of organic foulants, iron and manganese ions, chlorine and other oxidizing agents, and suspended solids degrade the resin inside the water softener. Water pre-treatment is an important preventative maintenance step. Organic foulants mechanically block the resin and prevent proper water flow through the resin. [12] Iron and manganese ions add to the hardness of water and in their trivalent state they permanently block resin sites. [12] Chlorine and other oxidizing agents attack the polymer linkages decreasing the efficiency of the resin. [12]

Water supplied by municipalities undergo extensive pre-treatment by the municipality's public utilities or public works department. Most municipalities have information on the pre-treatment provided to the water supply on their website along with a water quality report about the chemical makeup of the water supplied. If a facility receives water from its municipality and they pretreat the water supply, no additional pre-treatment is usually required. If water is supplied from a private well, organic foulants are unlikely, but iron and manganese are possible and can be removed with the use of activated carbon filters, oxidizing filters or polyphosphate pretreatment. [12] If water is supplied from an open source (rivers, lakes etc.), there may be organic foulants which can be removed with activated carbon filters or with chlorine. [12] A chemical analysis test can be conducted to determine the appropriate water pre-treatments. Ensuring the raw incoming water to the softener has low concentrations of foulants helps ensure resin health and maintains the softener efficiency.

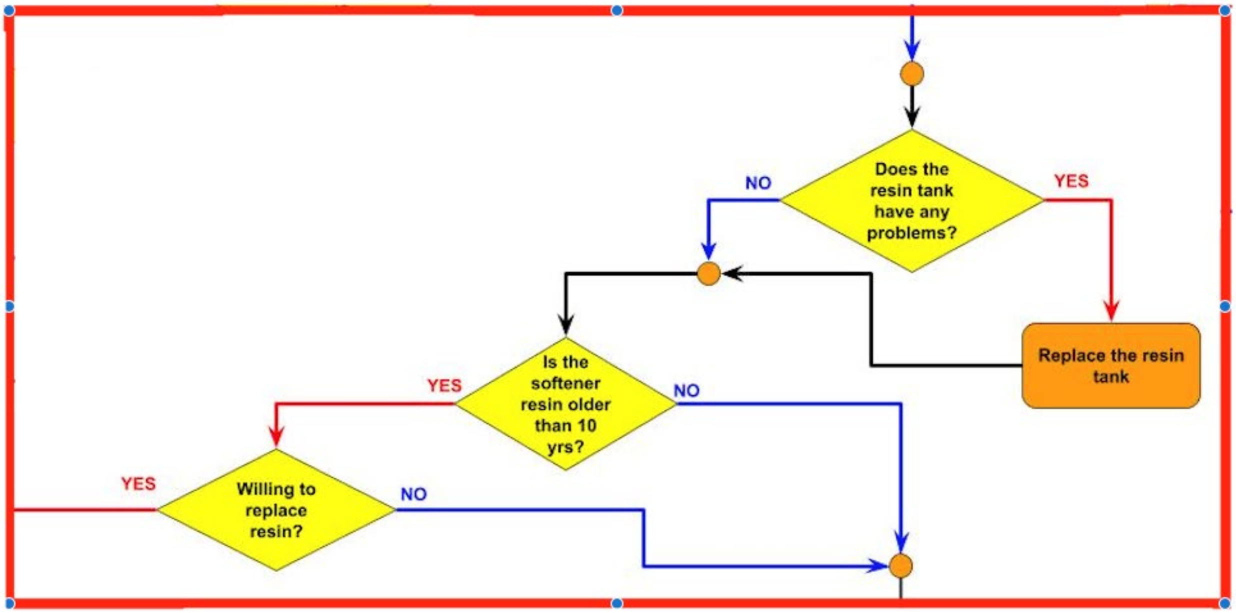


Figure 5: Softener optimization flowchart section for the resin.

Does the resin tank have any problems?

The ion-exchange resin resides is in a resin shell/tank. If there are any problems with shell/tank this could cause resin loss, water loss and inconsistent flow rate. If the pressure differential across the resin is too high, this indicates a resin shell/tank problem such as leakage or valve blockage. Any mechanical problems should be repaired, or the resin shell/tank should be replaced to make sure the softener is working in its optimal condition.

Is the softener resin older than 10 yrs?

The age of the water softener and the resin bed should be determined. The resin bed is made of many small round beads. Over time, the resin beads are cracked into smaller pieces due to agitation during the regeneration process. The cracked beads are lost during the backwash phase of the regeneration process. [13] Additionally, foulants can cause excess degradation of the resin as mentioned in the pre-treatment section above. This resin loss reduces the exchange capacity of the softener leading to more frequent regenerations and a reduced efficiency. Around 1-3% of the resin bed volume is lost annually. When this loss is compounded across 10 years, it translates to a resin bed volume loss of 10% - 27%. [13] Softeners that have high foulant concentrations and/or regenerate more frequently may lose more resin each year and need to be replaced sooner. [13] Replacing the resin bed every 10 years, ensures that the resin bed is restored to its original operating capacity. [13] Replacing the resin decreases the number of regenerations allowing the softener to return to its original capacity and allowing the softener to operate at a higher salt efficiency. [13]

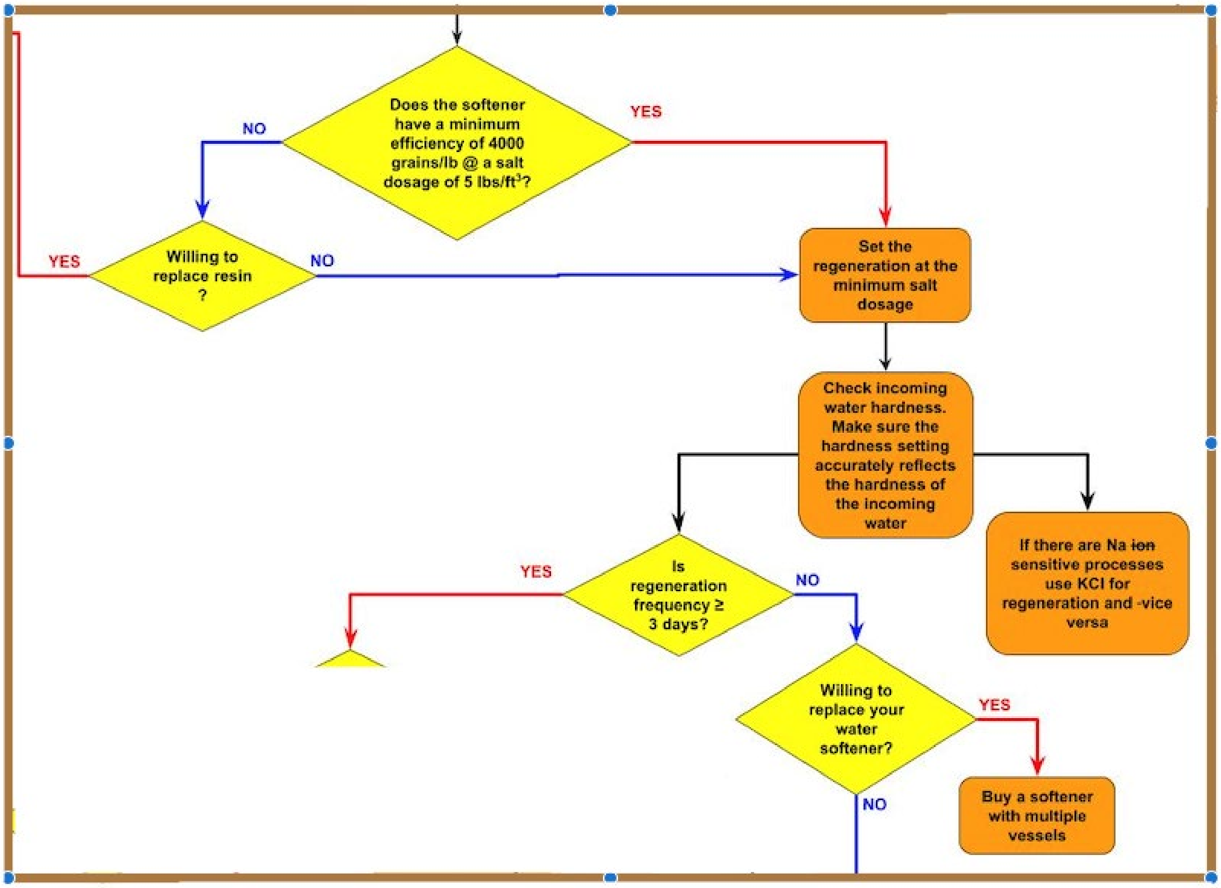


Figure 6: Softener optimization flowchart section for the softener efficiency and settings.

Does the softener have a minimum efficiency of 4,000 grains/lb at a salt dosage of 5 lbs/ft^3?

Water softeners should operate at a minimum efficiency of 4,000 grains/lb at a salt dosage of 5 lbs/ft^3 (see Figure 6). Identifying the type of resin in the water softener and accessing the technical data sheet will help determine the efficiency and salt dosage. The technical data sheet should include a graph which maps the relationship between salt dosage (lbs of salt/ft^3 of resin) and the operating capacity (grains/ft^3 of resin). Using Equation 2, the salt efficiency can be found.

$$Salt\ Efficiency = \frac{Operating\ Capacity}{Salt\ dosage}\ \frac{\left(\frac{gr}{ft^3}\right)}{\left(\frac{lbs}{ft^3}\right)} \qquad 2$$

The salt efficiency is the grains of hardness removed per pound of salt used in the regeneration process. If the data sheet is not available, then calculate the number of grains of hardness removed in a certain period (can be done by multiplying the amount of water softened in a period by the Feed Water Hardness setting) and divide this by the amount of salt consumed in the same period, as seen in Equation 3.

$$Salt\ Efficiency = \frac{(Feedwater\ Hardness) * (amount\ of\ water\ softened)}{(amount\ of\ salt\ consumed)}\ \frac{(gr) * \left(\frac{gal}{time}\right)}{\left(\frac{lbs}{time}\right)} \qquad 3$$

Ensuring that the softener operates at a high salt efficiency optimizes the softener and reduces salt usage. [8] To achieve a high salt efficiency the salt dosage can be decreased until the softener hits an efficiency of 4,000 grains/lb. [8] The salt dosage should not go below 5 lbs/ft^3 because this would improperly regenerate the resin. [8, 14] If the current resin is unable to attain a minimum efficiency of 4,000 grains/lb at 5 lbs/ft^3, then consider replacing the resin with a higher efficiency resin. If the resin can attain an efficiency of 4,000 grains/lb, then changing the salt dosage would mean changing the regeneration setting: either the brine draw time or brine refill time (depending on the softener).

The example shown below illustrates two cases, one where the softener operates at a high efficiency and one where it operates at a low efficiency. For this example, the resin in the softener is DOWEX HCR. The operating capacity for this resin at different salt dosages is in Figure 7. This example specifically looks at a high salt dosage of 10 lbs/ft^3 and a low salt dosage of 5 lbs/ft^3 and assumes a resin volume of 1 ft^3, a water hardness of 24 gpg, and 15,000 gal of water softened annually.

To calculate the salt use and water use, first the operating capacity in grains per cubic foot of resin is determined from Figure 7. Then the operating capacity is converted to gallons with Equation 4.

$$Capacity\ (gal) = \frac{Capacity\ (gr/ft^3) \times resin\ volume}{Hardness} \tag{4}$$

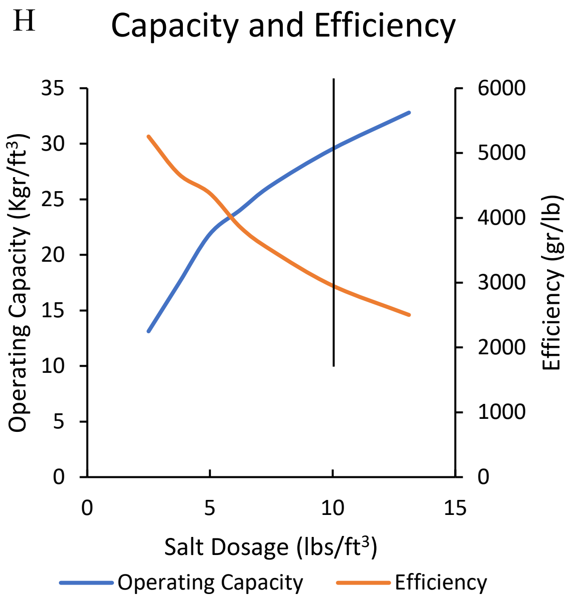
The total number of regenerations performed annually is calculated based on the quantity of water softened annually and the operating capacity in gallons (see Equation 5).

$$Annual\ regenerations = \frac{Water\ softened}{Capacity\ (gal)} \tag{5}$$

The annual salt use is calculated based on the annual number of regenerations, resin volume, and salt dosage with Equation 6 and the annual water use is calculated based on the annual number of regenerations and the water used per regeneration with Equation 7. The water used per regeneration depends on the flowrate and duration of each regeneration phase (Backwash, Brine Rinse, Slow Rinse, Rapid Rinse and Brine Refill). This example assumed 100 gal of water used per regeneration at a salt dosage of 10 lbs/ft^3 and 98 gal of water used per regeneration at a salt dosage of 5 lbs/ft^3. The lower salt dosage requires less brine which results in less water used per regeneration. The efficiency at each salt dosage was calculated with Equation 2 and is shown in Figure 7.

$$Annual\ salt\ use = Annual\ regenerations \times resin\ volume \times salt\ dosage \tag{6}$$

$$Annual\ water\ use = Annual\ regenerations \times water\ use\ per\ regeneration \tag{7}$$



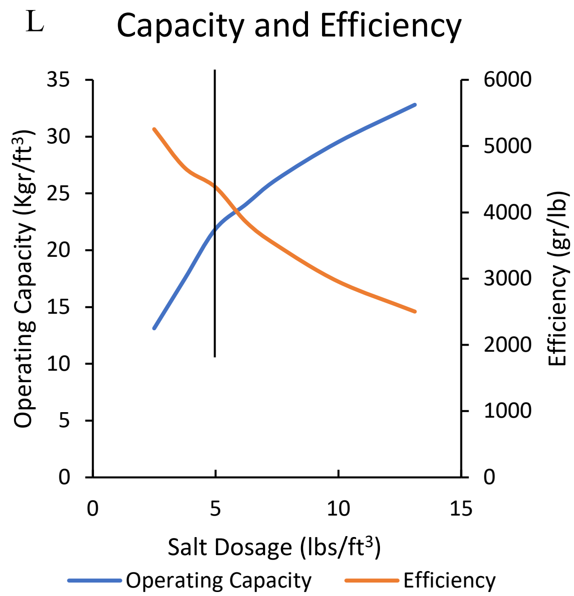


Figure 7: Operating capacity and efficiency curve of the DOWEX HCR resin for a high salt dosage (H) and a low salt dosage (L). [15]

High Salt Dosage		Low Salt Dosage	
Salt dosage	**10 lbs/ft^3**	**Salt dosage**	**5 lbs/ft^3**
Capacity (from Figure 8)	29,500 gr/ft^3	Capacity (from Figure 8)	21,800 gr/ft^3
Capacity (Eq. 4)	1,229 gal	Capacity (Eq. 4)	908 gal
Annual regenerations (Eq. 5)	12	Annual regenerations (Eq. 5)	17
Annual salt use (Eq. 6)	**120 lbs**	**Annual salt use (Eq. 6)**	**85 lbs**
Water use per regeneration	100 gal	Water use per regeneration	98 gal
Annual water use (Eq. 7)	**1,200 gal**	**Annual water use (Eq. 7)**	**1,670 gal**
Efficiency (Eq. 2)	**2,950 gr/lb**	**Efficiency (Eq. 2)**	**4,360 gr/lb**

As seen in the example, lowering the salt dosage increases the efficiency and reduces salt use. However, lowering the salt dosage usually results in a water expense since the number of annual regenerations increases (the increase in regenerations outweighs the decrease in water use per regeneration). Ideally, lowering the salt dosage is implemented with other optimizations to offset any increase in water usage.

Check water hardness and accurately program the settings:

Accurately setting the hardness of the incoming raw water ensures that pre-mature regenerations are not triggered, decreasing the number of regenerations. Fewer regenerations translate to reduced salt and water usage. If the water is supplied by a municipality, check the annual water quality report for the hardness and program the control head of the softener accordingly. If the water is from a private source, conduct a chemical analysis on the source and then program the total hardness accordingly. If conducting a chemical analysis is a financial constraint, there are drop-count titration kits which measure the total hardness of the water. As the name suggests, the kit includes a titration kit wherein the number of drops of titrant is directly proportional to the hardness. [16]

Are any processes sensitive to Na^+ or K^+?

Identifying if any of the processes consuming soft water are sensitive to sodium ions or potassium ions or both is important. For processes that are sensitive to ions, like water at research facilities, it is important that the water does not contain those specific ions. If a process is sensitive to either sodium or potassium ions, then the regenerant used by the softener should reflect the sensitivity i.e., use NaCl if there are potassium sensitive processes and vice versa. If there are processes that are sensitive to sodium ions and potassium ions or any dissolved particle, then a water softener and a Reverse Osmosis system are used. For example, a boiler requires pure water, and any dissolved particles result in fouling which leads to inefficient heating and wastes energy. When possible, use NaCl as a regenerant, since using KCl requires more salt. A system that uses NaCl releases 13% - 15% less chloride when compared to a system that uses KCl. [8]

Is regeneration frequency ≥ 3 days?

The number of times each resin bed regenerates, including both automatic regenerations and off-cycle or manual regenerations, should be determined. As mentioned before, more frequent regeneration increases degradation and fouling of active sites in the resin. Resin degradation reduces exchange capacity which decreases the efficiency of the resin. Ensuring the regenerations occur at intervals greater than or equal to every 3 days minimizes resin degradation, leading to a lower overall resin loss per annum [8]. This may mean resizing the current softening setup. Resizing the softening system, can either mean adding extra resin beds until the regeneration frequency is above 3 days or replacing the current softening system with a higher resin volume system. Apart from preserving resin health, increasing the time between regenerations leads to salt and water savings because fewer regenerations are necessary.

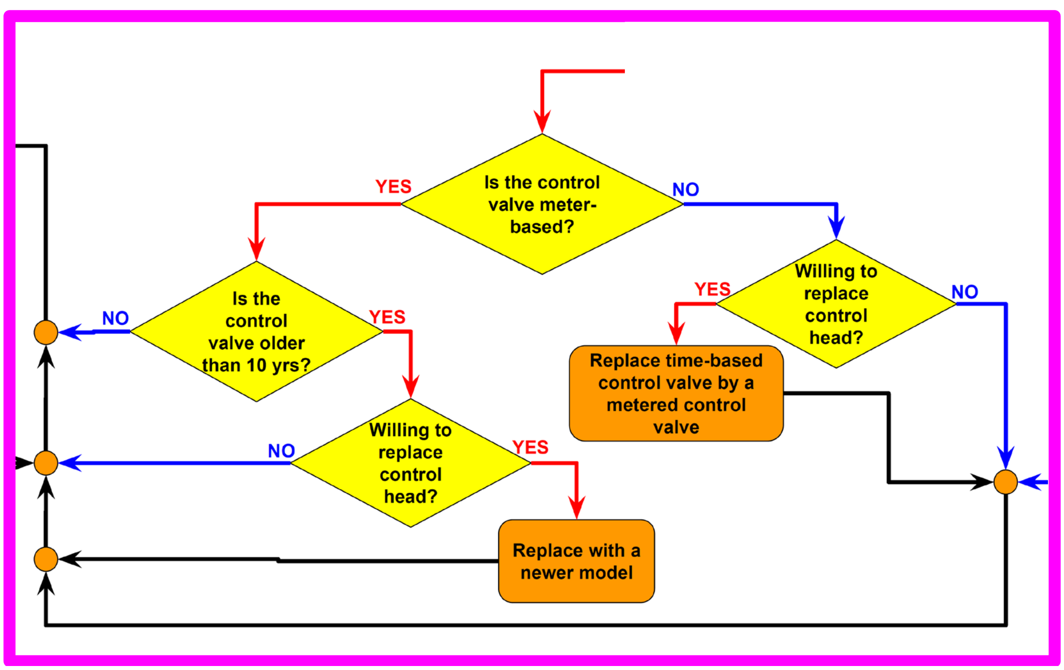


Figure 8: Softener optimization section for the control valve.

Is the control valve meter-based?

There are two types of control heads on softeners 1) Timer based and 2) Meter based. A Timer-based control head regenerates after a certain amount of time while a metered control head triggers a regeneration after a certain volume of water has been softened. Timer control heads either regenerate pre-maturely leading to salt wastage or regenerate late leading to hard water in the process system. [10] Using metered control heads prevents the common pitfalls encountered with timer-control head usage. [10]

Is the control valve older than 10 yrs?

It is important to find out how old the control head is and when it was last inspected. Metered control valves experience wear and tear and if any part of the control head is damaged it should be replaced to avoid impacts on the capacity of the unit and the regeneration cycle. The older a control head gets, the more often it will experience problems and the necessary parts for fixing it will become scarcer. Replacing an old, metered control head with a new one prevents any problems that could originate from the control head. [17]

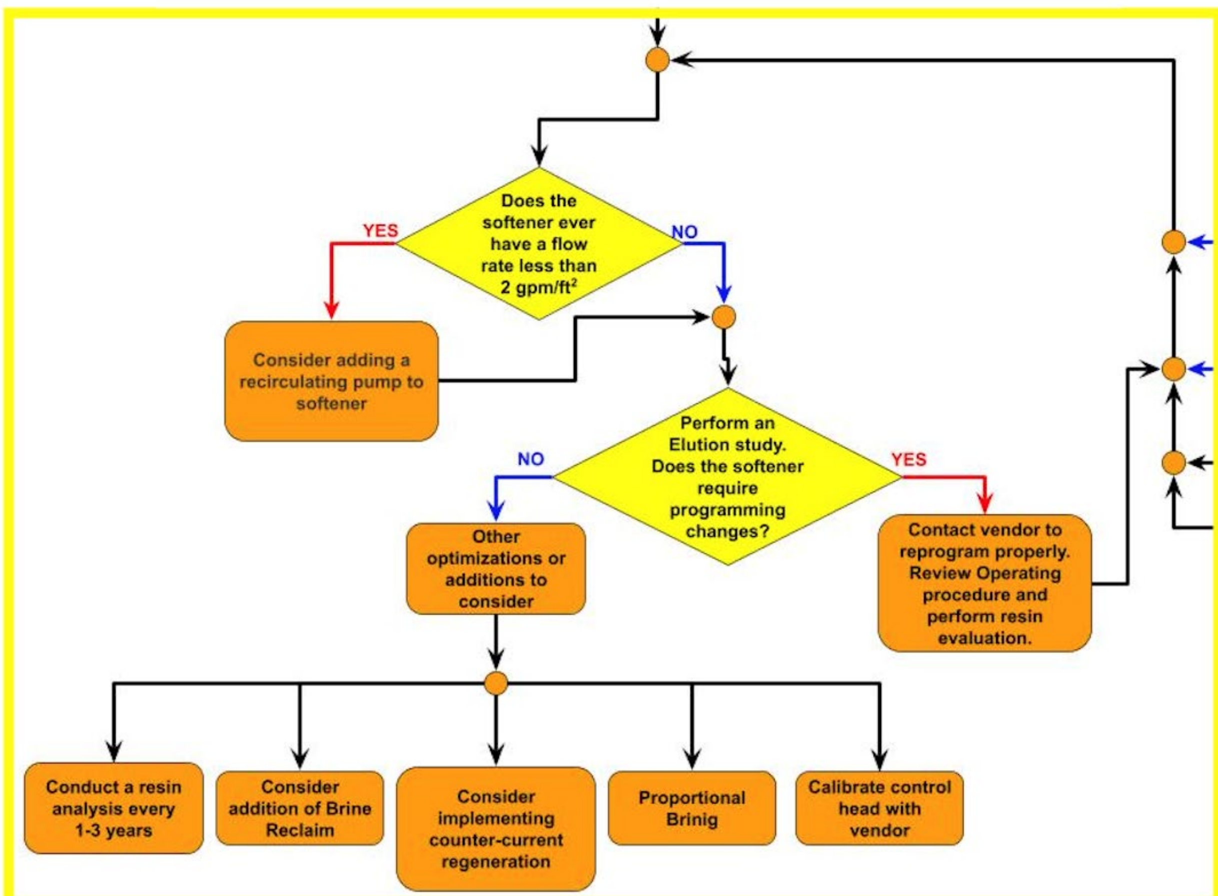


Figure 9: Softener optimization flowchart section for softener flowrate, elution studies, and other optimizations.

Does the softener ever have a flow rate less than 2 gpm/ft^2?

The minimum flowrate of water through the softener should be checked. If the softener experiences low flowrates (less than 2 gpm/ft^2), channeling occurs. Channeling is when the water takes the same path in the resin bed. Channeling does not allow a softener to use its complete capacity because water flowing through the same path will only visit exhausted resin and will not be softened. To use the full capacity of the softener, recirculating pumps can be used. Using a recirculating pump ensures a reliable supply of soft water and proper use of the softener's full capacity.

Perform an elution study - Does the softener require programming changes?

An elution study is a diagnostic tool which measures the effectiveness of the regeneration process. To perform this study, a salometer is required. A salometer is a form of hydrometer which measures the percent brine saturation in a sample. Using a salometer, timer, and graduated cylinder, the concentration of the outgoing brine is observed throughout the Brine & Slow Rinse phase and plotted as a function of time. [18, 19, 20] Analyzing the graph illuminates potential problems during the regeneration process and can indicate a necessary change to Brine Draw Time, Brine Rinse Time, Salt Dosage or Slow Rinse Time. Refer to Appendix B, for more detailed instructions about how to perform an elution study and interpret results.

Other Optimizations or additions to consider:

If the softening system has been fully optimized according to the flowchart, the following optimizations or additions can be considered for further salt savings and reduced wastewater chloride loading (see Figure 9).

Resin Analysis:

A core resin analysis helps gauge the amount of degradation the resin bed has undergone. To perform a core resin analysis, a cross-sectional sample of the resin is taken and then microscopically analyzed for the presence of cracked or otherwise degraded resin. Performing a resin analysis every 1-3 years, depending on the use of the softener, will give a good idea of the health of resin and the capacity settings of the unit can be adjusted accordingly. Performing a resin core analysis helps establish a timeline for replacing the resin bed and it may also indicate problems caused by foulants.

Brine Reclaim:

Brine reclaim is a system added to the regeneration process which collects excess brine to reuse in the subsequent regeneration process. During the regeneration cycle up to 2/3rd of the salt used is wasted, this opens the possibility of reclaiming that portion of brine to use in the next regeneration process. The first equivalent quantity of brine (first equivalent quantity corresponds to 2 quantities of sodium ions for each calcium or magnesium ion) releases most of the hardness from the resin and re-saturates it with sodium ions. [14] Therefore, when the reclamation process is conducted, the first equivalent quantity is not collected as it would contain significant quantities of calcium and magnesium ions. As the hardness in the discharge water decreases, this portion of the waste brine is collected and reused. When the reclaimed brine is used, it does not need to be diluted as it is mostly in the 8-10 wt% brine concentration range. [14] Brine reclaim has the potential to reduce water and salt usage by 35-40% and 25-40%, respectively. [11]

The effectiveness of this process depends entirely on whether the correct quantity of brine is collected and saved. Brine reclamation should only be implemented when the salt dosage is more than 8 lbs/ft^3. At dosages less than 8 lbs/ft^3, the window to collect the useful brine is extremely small and it is difficult to reliably collect the water. If implemented properly, almost 30% of the brine can be reclaimed and reused in the next regeneration. [14] Given the very particular window of brine collection, it is necessary that a brine reclamation system is properly calibrated and maintained. The maintenance would include making sure the accurate portion of brine is reclaimed.

If the current operating system has a resin that can facilitate a salt efficiency of at least 4,000 gr/lb at a salt dosage of 8 lbs/ft^3, then a brine reclaim system should be considered as it would lead to salt and water savings without the drawbacks associated with lowering the salt dosage (increased number of regenerations and water use). [14] If a brine reclaim system is selected, some changes must be made to the brine refill time to ensure no excess water is added. If there is a RO system after the softener, then there is potential to reuse the RO reject for the softener regeneration. Before attempting to use RO reject, make sure that the RO reject water does not have a high concentration of foulants in it.

Calibrating the Control Head:

If the softener has a metered control head, over time the metered control head loses calibration meaning it will not accurately record remaining capacity of the softener. If the remaining capacity value shown is above the actual remaining capacity, this will trigger pre-mature regenerations and lead to salt and water expenditure. [14, 17] If the value shown is below the actual softened volume, then this will lead to poor softening of the raw incoming water towards the end of the unit capacity. Regular calibration of the meter in the control head ensures efficient salt and water use. Calibrate the control head every 1-3 years to ensure optimal performance. [14, 17]

Counter-current Regeneration:

In a counter-current regeneration system, the regenerating brine flows in the opposite direction of the flow of hard water. For the same salt dosage, performing a counter-current regeneration, allows the resin to operate at a higher capacity, thereby reducing the number of regenerations performed by the water softener leading to salt and water savings. Counter-current regeneration systems, need 35%-40% less salt and using 40% less water. [11] One of the major drawbacks of counter-current regeneration is a higher rate of resin volume loss, thereby accelerating the resin replacement timeline. However, this can be countered by placing a filter along the softener drain and collecting the resin that washes out and putting the collected resin back in the softener. [11, 14]

Proportional Brining:

In single and parallel water softening systems, regenerations do not occur at the end of the unit capacity (excluding reserve capacity), instead they regenerate early to ensure no hard water is supplied. [21] Given that a certain amount of the unit capacity is remaining (along with the reserve capacity), there is a portion of resin that does not need to regenerate. A proportional brining system ensures that the regeneration is tailored to account for the resin that is not exhausted. [21] A proportional brining system considers the full capacity of the unit versus the used capacity before regeneration and then accordingly adjusts the brine refill time or brine draw time. This system can lead to salt and water savings and prevent over-salting in the regeneration process. [21]

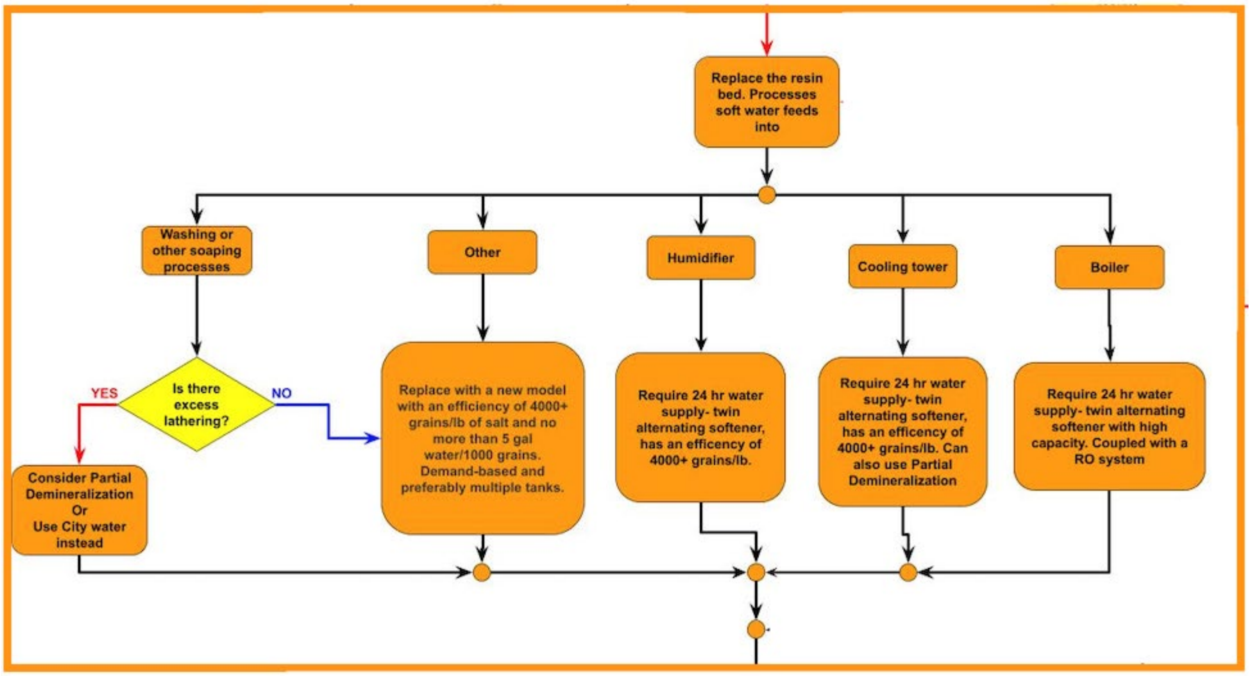


Figure 10: Softener optimization flowchart for specific processes.

Processes soft water feeds:

The process that the soft water feeds into may determine how to set-up the system to ensure salt and water optimization. Some possible options are listed below.

Boiler:

Boiler operations require pure water with no dissolved solids in it. The presence of dissolved solids in a boiler will lead to deposition on the boiler. The deposition decreases boiler efficiency resulting in increased energy usage. [22] If the water supplied is from a private source, a softener is combined with a RO system to ensure pure water is supplied to the boiler operations. If the water supplied is from a municipality, a standalone water softener is sufficient. In most industrial set-ups, boilers are operated continuously thereby demanding a continuous supply of soft water. To cater to this need, an alternating softener set-up should be used. [22]

Cooling Tower & Humidifier:

Cooling towers are an important part of an industrial complex, depending on the need these are operated either seasonally, or throughout the year. Cooling towers experience water loss in the form of evaporation. However, this leads to an increase in the water hardness which can form scale. [23] If the cooling towers are operated continuously then an alternating softening system, should be used. This above solution also applies to a Humidifier system. Another solution to prevent deposition in cooling towers is to add sulfuric acid to the water supply. The sulfuric acid reacts with the calcium carbonate (hardness) releasing carbon dioxide and forming aqueous calcium sulfate (a more soluble salt, which will not foul). Use of sulfuric acid in cooling tower operations is only advised if most of the soft water is dedicated to the cooling tower. The use of sulfuric acid, while not a widespread practice, will eliminate additional chloride loading in wastewater and result in salt and water savings. Another practice observed for cooling towers is partial de-mineralization. [23] This is a process wherein only a portion of the water heading the cooling tower is softened and the other portion of the water supplied is hard water. This reduces the overall hardness of the water supplied to the cooling tower without completely softening it.

Washing/Soaping processes:

Most washing and soaping processes require soft water. Soft water allows for more efficient soap use and prevents the formation and deposition of soap scum. Softening systems must be designed to accommodate the water supply needed for these processes. [8] While hard water can prevent proper lathering, soft water can lead to excess lathering. If soaping and washing processes experience excess lathering, it is a sign of over-softening. This can be remedied by converting the water supply to these processes to city water or using a combination of soft water and city water. [24]

Other:

For any process using a softener, ensure that the resin is operating at minimum efficiency of 4000 grains/lbs at a salt dosage of 5 lbs/ft^3 while regenerating at a minimum frequency of 3 days. [8]

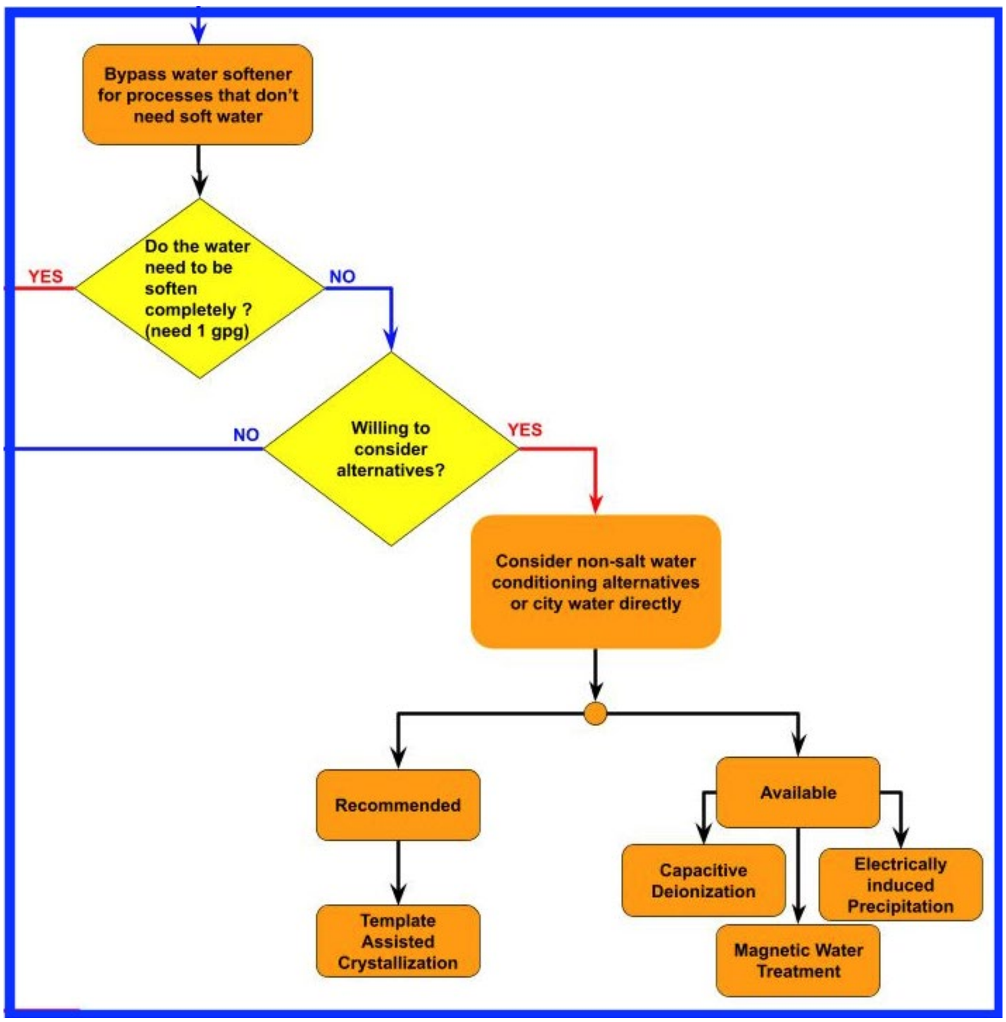


Figure 11: Softener optimization flowchart for non-salt alternatives.

Non-salt Conditioning Alternatives:

Template Assisted Crystallization (TAC)

Template Assisted Crystallization is a relatively new mode of water conditioning. TAC was primarily developed to prevent scaling from hard water. In a TAC system, hard water passes through polymeric beads acting as catalytic nucleation sites for the formation of crystals. [3] As the water passes through the beads, the ions fall into the nucleation sites and grow into microscopic crystals, which are then released back into the water. [3] Refer to Figure 12, for the catalytic nucleation sites employed by a TAC system. These microscopic crystals act as better deposition environments than the piping walls, in scale-growing environments. [3] TAC system is a physical process since the hardness is converted from an ionic aqueous state to a solid crystalline state. The pros and cons of this technology are in Table 1.

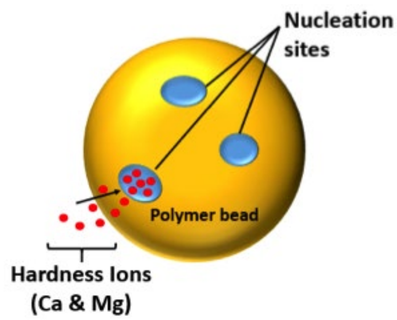


Figure 12: The polymeric nucleation catalyst important to TAC. Image from Heger. [25]

Table 1: Advantages and Disadvantages of a TAC system [3]

Pros	Cons
• No additional chloride loading • No water usage (since no regeneration process) • Smaller operation and maintenance costs • Comparable scale reduction capabilities to Ion-exchange softeners	• Hardness is not removed but transformed – soft scale formation possible • Catalyst media replaced every 3-4 yrs • Ineffective on standing water systems • Aesthetically unpleasant • Technology still developing – unsure of industrial capabilities

Magnetic Water Treatment (MAG)

Magnetic Water Treatment is a physical separation process. MAG systems employ a wire coil around a pipe connected to a transformer. Refer to Figure 13, for a schematic of a MAG system. When current is passed through the wire, a magnetic field either oriented with the flow or against the flow of the pipe is created which will cause the cations to move to the center of the pipe and the anions to move to the wall of the pipe. [3] When the current direction is changed the field direction is switched, causing the cations and anions to collide with each other at a higher frequency and energy allowing the formation of minute crystals. [3] The pros and cons of this technology are in Table 1.

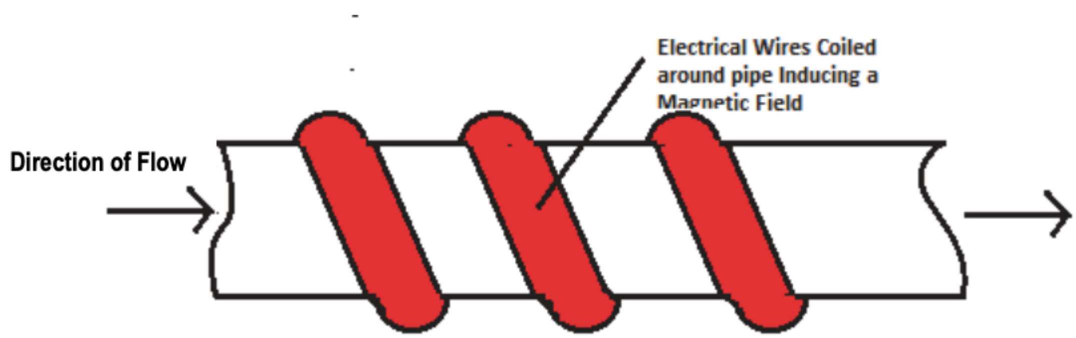


Figure 13: Schematic of the magnetic water treatment from Fox et al. [3]

Table 2: Advantages and Disadvantages of a MAG system [3]

Pros	Cons
• No additional chloride loading • No water usage (since no regeneration process) • Smaller operation and maintenance costs – extremely affordable	• Hardness is not removed but transformed – soft & hard scale formation possible • Can only reduce scale formation by 50% • Cannot be used independently for water conditioning

Electronically Induced Precipitation (EIP)

Electronically Induced Precipitation systems use the electromagnetic properties of hardness ions to condition water. Using an electric field, the hardness ions are precipitated on an electrode, which is then cleaned. [3] Microscopic particles also remain suspended in the water which act as better deposition environments than the piping walls, in scale-growing environments like high temperature environments. The pros and cons of this technology are in Table 3.

Table 3: Advantages and Disadvantages of an EIP system [3]

Pros	Cons
• No additional chloride loading • No water usage (since no regeneration process).	• Hardness is not removed but transformed – soft & hard scale formation possible • Can only reduce scale formation by 50% • Cannot be used independently for water conditioning • High capital, operational and maintenance cost

Capacitive Deionization (CDI)

Capacitive Deionization is relatively new technology in the field of water treatment and conditioning. In a CDI system, water is passed between two charged electrodes with high surface area and adsorption capabilities, so that the cations move towards the negative electrode and the anions move towards the positive electrode and are absorbed into the electrode surface. [3] Once the electrode surface becomes saturated, a backwash phase occurs where the charge on the electrodes are reversed while the water flows through the system. This ensures that the adsorbed ions are repulsed by the electrode and carried away by the water into the wastewater discharge. [3] Refer to Figure 14, for an illustration of the conditioning process carried out in a CDI system. The pros and cons of a CDI system are in Table 4.

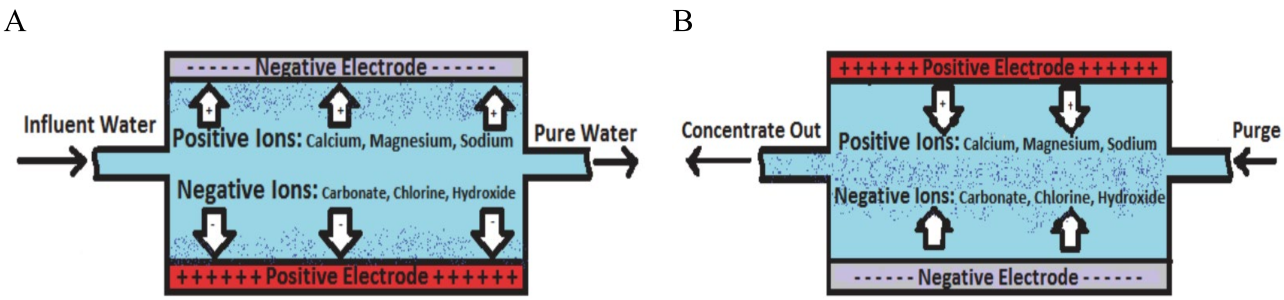


Figure 14: (A) The separation process performed by CID systems. (B) CID system backwash step from Fox et al. [3]

Table 4: Advantages and Disadvantages of a CDI system [3]

Pros	Cons
• No additional chloride loading • Minimal water usage (only backwash phase) • Removes hardness • Comparable scale reduction capabilities to TAC systems and Ion-exchange softeners	• High capital, operational and maintenance cost. • Lack of widespread data on performance in an industrial and commercial setting

Reverse Osmosis (RO)

A Reverse Osmosis (RO) system is one of the most widely known and used water conditioning systems. In a RO system, the raw incoming water is passed through a semipermeable membrane. The membrane is selectively permeable meaning it only allows water to pass through leaving the contaminants on the other side of the membrane. [26] Due to the selective nature of the membrane, it can filter out almost any, if not all, contaminants present in the feed water. This differs from an ion exchange softener which is specialized at exchanging ions, specifically cations. [26] Refer to Figure 15, for an illustration of this process. While there are different types of RO systems present, the central tenet revolves around the reverse osmosis membrane with variations arising due to additional filters being present in the system. The pros and cons of a RO system are in Table 5.

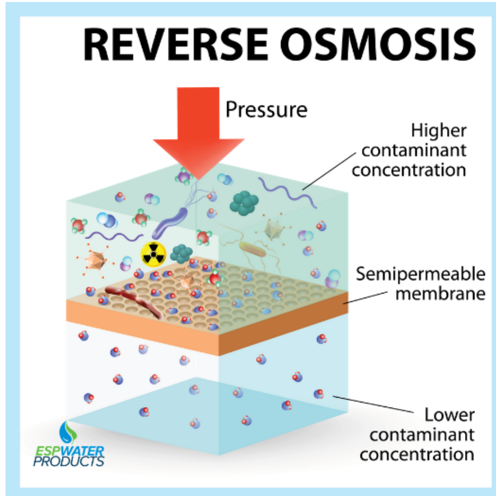


Figure 15: Illustration of a semi-permeable membrane in a RO system from ESP Water Products. [27]

Table 5: Advantages and Disadvantages of a RO system [26, 27]

Pros	Cons
• No additional chloride loading • Completely pure water supplied • Little to no scale growth	• High water and energy use • Periodic membrane cleaning and replacing • High capital, operational and maintenance costs • Implemented in conjunction with a water softener

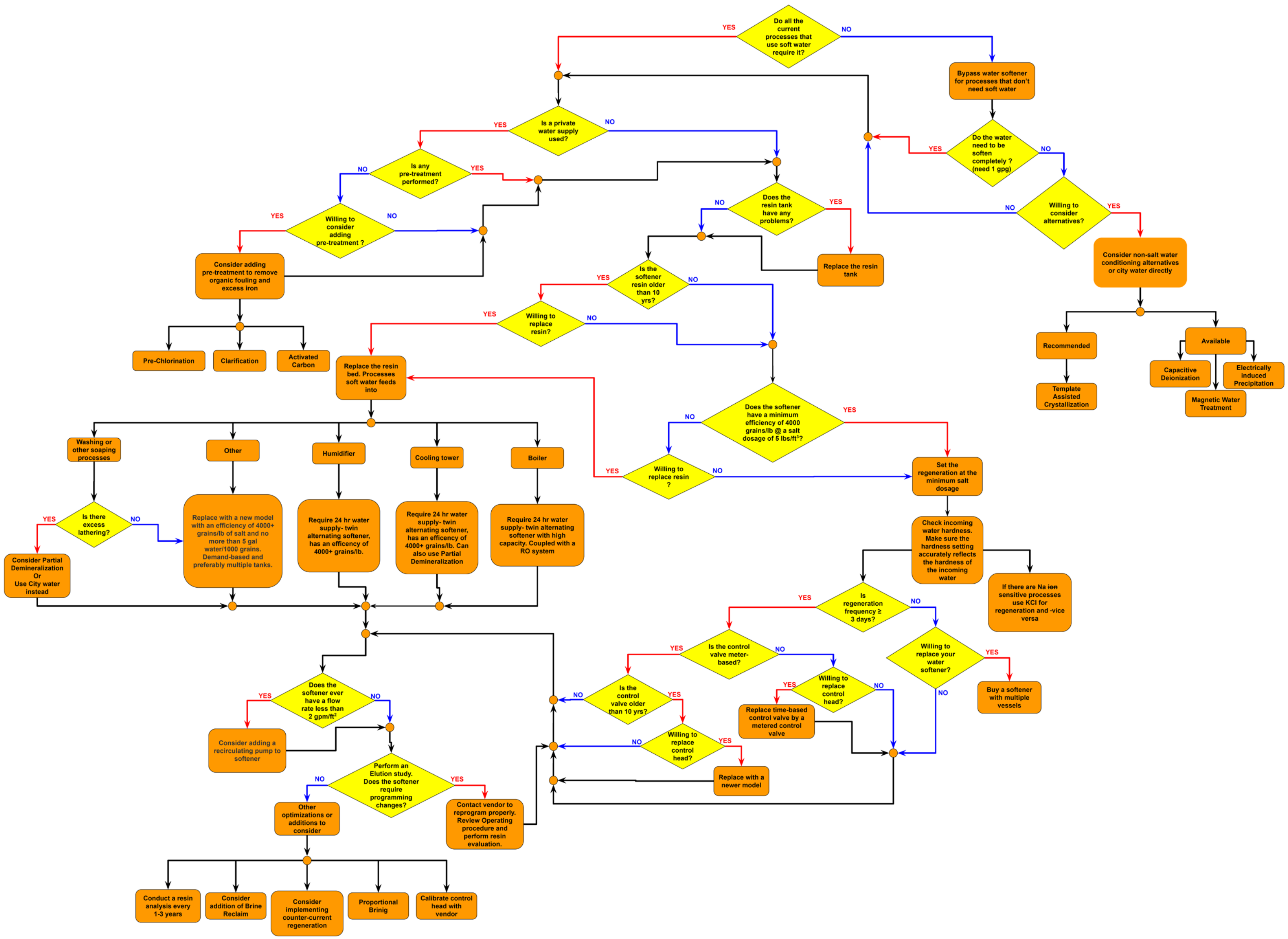
Site Visits

When performing a site visit, a pre-visit questionnaire (Appendix C) was sent to the site at least a week in advance to be returned the day of the site visit or earlier. Pictures of the control head atop each softening unit were also requested at least 2 days before the site visit, so that the instruction manual for the control head could be found and studied to access the softener settings. During the site-visit itself, the settings of each control head were accessed and recorded along with the programmed setting on specification sheets. Both were collected and compared to check for differences in the settings of the softener. The following settings were recorded:

1. Feed water Hardness
2. Unit Capacity
3. Reserve Capacity
4. Regenerant Flow
5. Regeneration Type
6. Salt Dosage
7. Backwash Time
8. Brine & Slow Rinse Time
9. Rapid Rinse Time
10. Brine Tank Refill Time

During site visits, any water pre-treatment before the softeners, alternative water conditioners, softener-sensitive processes and recent maintenance performed on the softener were identified. The dimensions of the softener were recorded (either from the softener specifications or measured). The dimensions can help determine an approximate resin volume if the exact volume is unknown. Information collection on site is streamlined using a Site-Visit questionnaire (Appendix C). At or after the site visit, the company that helped setup the water softener may be contacted with follow-up questions or requests for quotes. Once all the relevant information from the site visit questionnaires, site visit, and water softening company is obtained, the water softener optimization flowchart is used to find recommendations for the softening system.

Appendix A: Softener Optimization Flowchart



Appendix B: Elution Study Procedure and Data Interpretation

An elution study can be performed by staff onsite or by a water softening company.

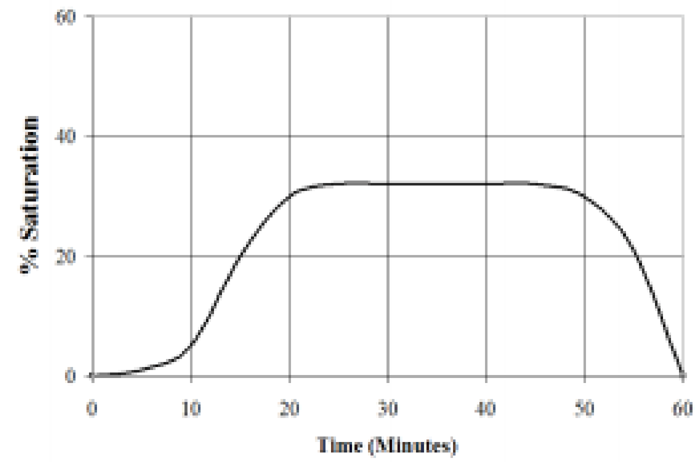
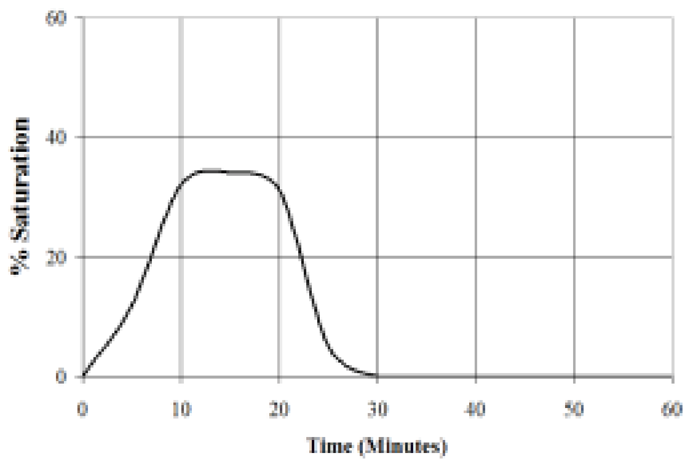
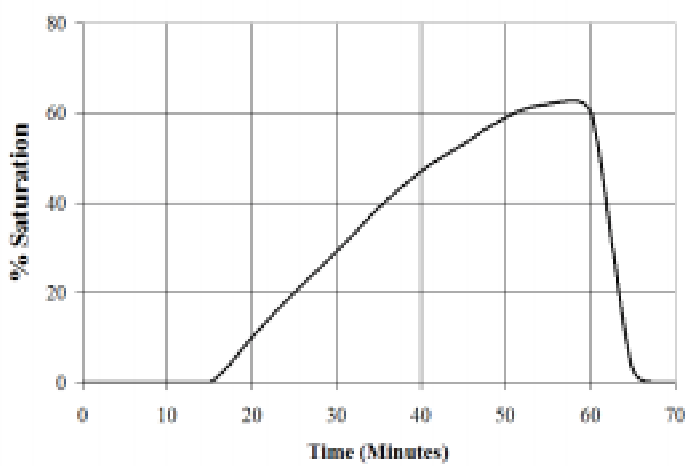
Tools Required:
- Salometer
- 250 mL Graduated cylinder
- Timer

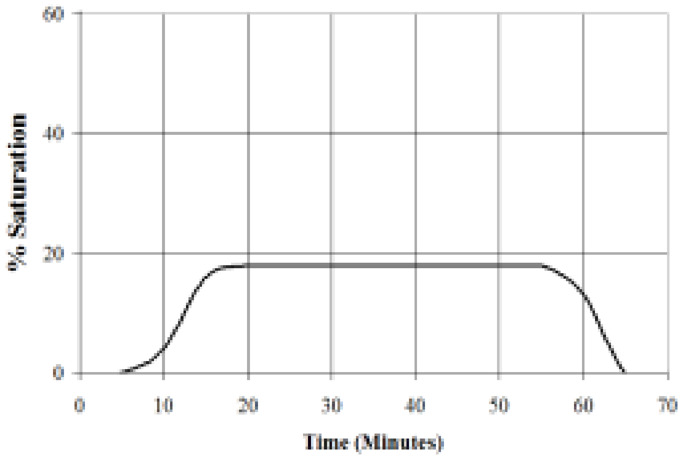
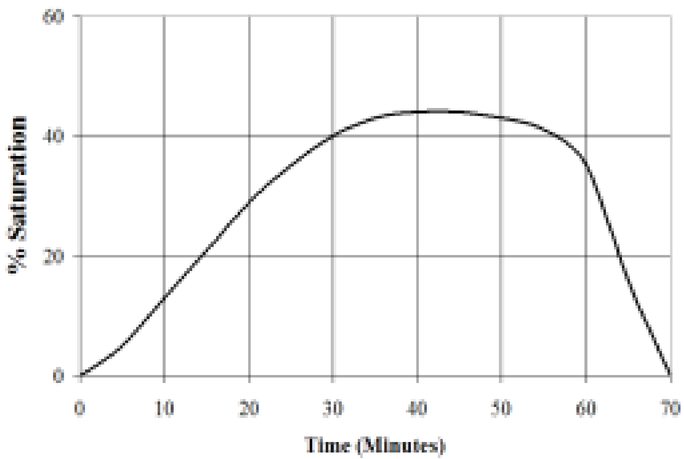
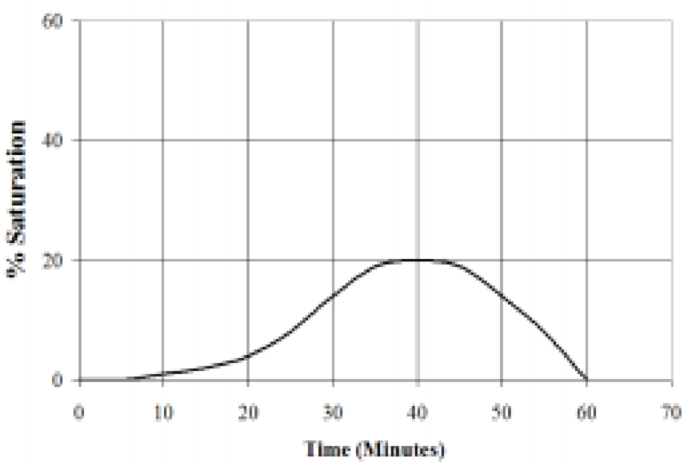
Sampling points:
- Brine tank
- Regeneration drain line - waste water discharge line

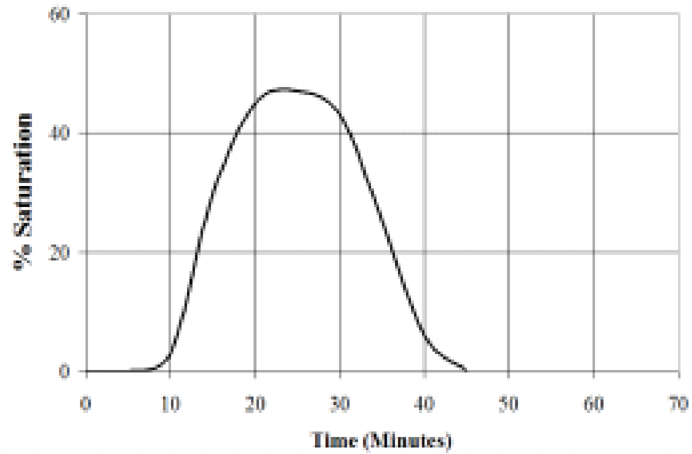
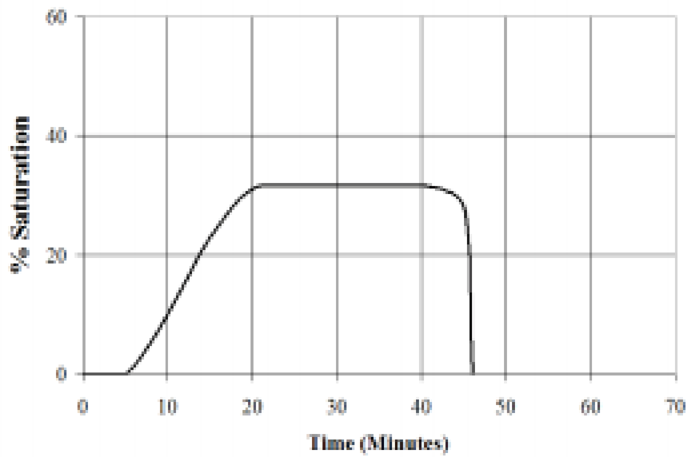
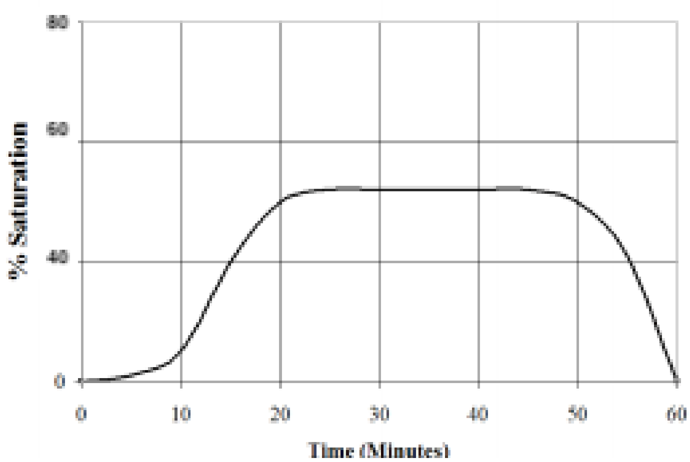
Procedure [18, 19, 20]:
- Measure the concentration of the brine in the brine tank using the salometer.
- Once the softener has started its regeneration cycle, wait for it to complete the backwash cycle, and then note the time when the brine cycle has started.
- Once the softener switches to brine cycle, take a water sample (enough to submerge the salometer, in the graduated cylinder) at the softener discharge before the discharge mixes with the other wastewater line.
- Find the salometer reading corresponding to the sample and record, then take another sample every 2 to 3 minutes until the reading has dropped below 5°.
- Make note of the time when the brine cycle, slow rinse and rapid rinse phases are completed
- Plot the collected data with time as the independent variable and the salometer degree reading as the dependent variable.

Understanding the results [18, 19, 20]:
- For an effective regeneration the constructed graph should have a salometer reading of 30° for at least 30 minutes. This translates to the resin bed having contact with an 8% salinity solution for at least 30 minutes.
- Looking at the graph from the above procedure, will give us clues as to which operational factors in the regeneration process could be optimized.
- The images shown below, from Softener Elution Study by James McDonald, show different potential elution graphs and possible problems.

Table 6. Different elution graphs and possible explanations for graphical behavior. Graphs from Softener Elution Study by James McDonald. [18, 19, 20, 22]

	Good regeneration that uses a minimal amount of salt
	Insufficient brine. Increase the brine draw time
	Using more salt than necessary. Reduce the brine draw and perhaps decrease slow rinse time

	Brine eductor, a device that uses flowing water to draw brine out of the brine tank, draws too slowly. It should be adjusted to draw brine faster
	Using more salt than necessary. Reduce brine draw to save salt
	Insufficient brine strength and contact time. Possible remedies are to increase brine draw time, decrease dilution water, and decrease slow rinse rate

	Brine eductor draws too quickly. It should be adjusted to draw brine more slowly
	Brining cycle interrupted by a premature rinse cycle.
	Regeneration using too much salt. Decrease salt dosage, too much brine draw.

An unconventional elution curve may not be able to pinpoint the exact cause of a problem, but it can confirm that a problem exists. Another elution study should be performed after any changes to confirm that the corrective measures are working.

Appendix C: Pre-Visit and Site-Visit Questionnaire

Pre-Visit Information Collection

Company: ______________ Information collected by: ________________ Date: ______

1. What is the water supply?

   Municipality ______________________

   Private source __________ What is the source? ______________________

   If known, what is the water hardness? ______________________

   Any water treatment before softener? ______________________

2. Make and Model of water softener: ___________________
   a. Who is the vendor? ________________
   b. Date of latest service: _________________
   c. Is there an on-site operator or technician? ________________
   d. Is there a manual available for the control head & softener? ___________________
      i. If digital, can you send it to me? ________________
3. Amount of water softened (appropriate units per day/week/month/year) : _______________
4. What processes or areas in the facility use soft water?

• • •	• • •

5. Are there any conditioning systems (i.e. Reverse osmosis?) _______________
   a. If yes, what type of system? _____________
6. Amount of salt used per day/week/month/year: ________________
   a. What kind of salt is used (NaCl, KCl, other) ___________
7. Are there any logs available?
   a. Regeneration frequency logs ______________
   b. Salt use logs _____________

Site-Visit Information Worksheet

Company: _______________ Date: _________

1. Hardness of incoming raw water (find 3 times):_____________________ (gpg or note units)
2. How old is the current water softener: _________________ (yrs or note units)
3. How many resin tanks are present: _________________
    a. Type of resin in softener: ________________
    b. Volume of each resin tank: ________________ (ft^3 or note units)
    c. Softening setup: Single Alternating Parallel Other:____________
4. What kind of control valve is used: Timer Metered DIR sensor Other:__________
    a. How often does regeneration occur? ___________________
    b. Type of Regeneration: Co-current Counter-current
    c. How much water is used during regeneration? ______________________
5. Current settings on the softener:
    a. Who programmed the settings? __________________
    b. Time: __________
    c. Hardness setting: _________ (gpg or note units)
    d. Salt Dosage: _______________ (lbs/ft^3 or note units)
    e. Capacity: ____________ (grains or note units)
    f. Other: ____________
6. Any Additional Features: Brine Reclaim Proportional Brining None
7. How often is the water softener serviced? _________________
8. Are any of the processes requiring soft water sodium sensitive? _______________
9. Hardness of outgoing water: ______________
10. How soft does the water need to be? ____________
11. Do you own a Salometer? ______________

Appendix D: Recognition

Special thanks to the following people for their input to this project:

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Culligan International
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