Wastewater

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Alternatives for addressing chloride in wastewater effluent

MPCA analyzes treatment options for salty parameters

MINNESOTA POLLUTION CONTROL AGENCY

Authors

Scott Kyser
Minnesota Pollution Control Agency Effluent Limits Section

Elise Doucette

Editing and graphic design

Jennifer Holstad

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Minnesota Pollution Control Agency

520 Lafayette Road North | Saint Paul, MN 55155-4194 |

651-296-6300 | 800-657-3864 | Or use your preferred relay service. | Info.pca@state.mn.us

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Executive summary

Minnesota has a growing salty water problem that threatens its fresh-water fish and other aquatic life, despite being more than 1,000 miles from the nearest ocean. Salt – from chloride – can also impact groundwater used for drinking. It takes only one teaspoon of salt to permanently pollute five gallons of water. Once in the water, there is no way to remove the chloride.

While this report focuses on chloride, other salty parameters of concern include:

- Total dissolved solids
- Bicarbonate
- Hardness
- Specific conductance

What is the water quality standard for chloride?

Our freshwater streams and lakes naturally have low levels of chloride. High concentrations of chloride are harmful to aquatic plants and animals.

Based on guidance from the U.S. Environmental Protection Agency and the levels of chloride shown to be toxic to fish, Minnesota has a water quality standard to protect aquatic life from chloride:

- Longer chronic exposure is a 4-day average of 230 mg/L
- Shorter term acute exposure is a 1-day average of 860 mg/L

Why do municipal wastewater plants have chloride in their discharge?

The answer starts with water hardness. People soften their water to make soaps lather more and prevent calcium buildup on appliances and fixtures. Point-of-entry ion exchange water softeners are widely used to treat water hardness in Minnesota. In order to ensure continued operation of a point-of-entry ion exchange softener, it must be periodically regenerated with high salt brine that contains chloride. This brine eventually drains to a municipal wastewater system. The cumulative loading from all the point-of-entry softeners in the sewershed contributes significantly to the high chloride concentrations in the wastewater plant discharge.

Where in Minnesota is chloride in wastewater a problem?

Chloride in wastewater discharge appears to be a problem in about 100 Minnesota communities, most of them in southern and western areas of the state. Chloride flows into wastewater treatment facilities from homes and businesses that use water softeners. Treatment facilities are designed to remove particles, like grit and sand, and to biologically degrade organic waste, such as food and human waste. Once chloride is dissolved in water, it cannot be removed by settling, or biologically degraded by standard treatment processes. The technology to remove chloride is available, but is costly. It would involve microfiltration and reverse osmosis (RO), which are the same treatment processes used to produce pure water used in laboratories.

How does the Minnesota Pollution Control Agency know it is a problem?

Water monitoring data also show that salt concentrations are continuing to increase in lakes, streams and groundwater across Minnesota.

Wastewater treatment facilities started monitoring for chloride and other salty parameters in 2009. The MPCA examined the data and found that about 100 facilities have the potential to contribute to levels of chloride higher than allowed by the standard. One common tool to reduce pollutants like chloride is to issue permits with effluent limits to control the amount of a pollutant in a facility.

What are the alternatives to comply with a chloride effluent limit?

There is no feasible alternative for treating chloride once it is dissolved into water. The current alternatives for treating chloride at Wastewater Treatment Plants (WWTPs) are infeasible for reasons ranging from engineering feasibility to cost to legal constraints.

Below are the three most feasible strategies for reducing chloride in source water coming to WWTPs, which are examined further in this document:

1. Upgrade residences and businesses to high efficiency point-of-entry softeners
2. Centralized lime softening and removing point-of-entry softeners
3. Centralized reverse-osmosis softening and removing point-of-entry softeners

Minnesota salty parameter water quality standards

Minnesota's water quality standards for salty parameters and their specific designated uses are summarized in Table 1.

Under the current regulatory structure, every surface water in Minnesota is presumed to be used for Industrial Cooling and Materials Transport (3C Classification), Irrigation (4A Classification) and Livestock and Wildlife (4B). Thus, 3C, 4A, 4B standards apply to every surface water.

The chloride standard in Table 1 needs to be considered for a discharge to any water in Minnesota, even if not designated as protected for aquatic life and recreation, because all streams – even those classified as limited resource value waters – eventually flow into a water protected for aquatic life and recreation (Classification 2).

Table 1. Minnesota water quality standards associated with the common major ions or salty parameters

Parameter	Units	Water Quality Standard Value	Use classification	Designated protective use
Chloride	mg/L	230 (Chronic)	2	Aquatic life and recreation
Hardness	mg/L as CaCO3	500	3C	Industrial Cooling and Materials Transport
Total dissolved solids	mg/L	700	4A	Irrigation
Bicarbonates	mg/L as CaCO3	250	4A	Irrigation
Specific conductance	µmho/cm	1000	4A	Irrigation
Total salinity	mg/L	1000	4B	Wildlife and livestock

The MPCA is legally required to determine if a discharge from facility with a National Pollutant Discharge Elimination System (NPDES) permit has reasonable potential to violate a water quality standard. If a facility has reasonable potential to exceed a water quality standard, then that facility must receive final permit limits for that parameter.

Total dissolved solids (TDS) and salinity are parameters that measure almost the same identical underlying parameter. For the purposes of effluent limit setting, the MPCA considers salinity and TDS as measuring the equivalent underlying parameter, which is ionic strength. The MPCA does not evaluate reasonable potential for the 4B Classification - 1,000 mg/L - salinity standard. The total salt content of a wastewater is always assessed against the 4A Classification - 700 mg/L - TDS standard because it is more protective than the 4B Classification.

Monitoring for salty parameters

In 2009, the MPCA began requiring mechanical WWTPs to monitor for salty parameters if they:

1. Discharged to a low dilution stream.
2. Received a waste stream from a concentrating treatment technology (RO, ion exchange, membrane filtration, etc.).
3. Received a waste stream from a food processing facility that uses saline-based density sorting. Stabilization ponds with a controlled discharge were exempted from the salty parameter monitoring.

The salty parameter-monitoring suite includes all major cations and anions. When these WWTP NPDES permits come up for re-issuance, the MPCA is required to analyze for reasonable potential to exceed state water quality standards in their downstream receiving waters.

The majority of the WWTPs that have or will receive a chloride or salty parameter limit fit into the categories below:

1. Municipal WWTPs that are not designed to treat chloride.
2. Have a substantial fraction of their customers using point-of-entry water softeners to reduce their drinking water hardness.
3. Do not receive substantial chloride loading from concentrating technologies or food-processing facilities using density based sorting.
4. Are not designed to treat or remove any salty parameter.

Salty parameter sources of loading to WWTPs

In general, salty parameter loading fall into three categories:

1. Naturally occurring salts in the source water
2. Anthropogenic salts in the source water
3. Anthropogenic salts after the source water has been treated

Loading from salts naturally occurring in source water

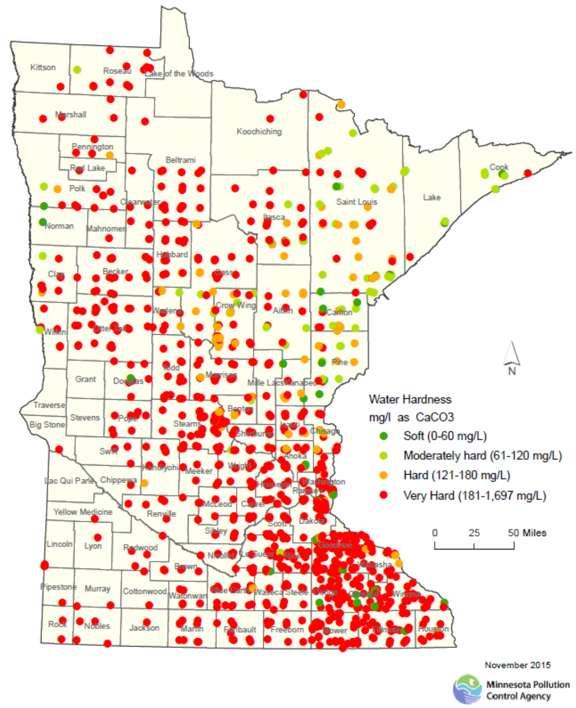
Source water to a Minnesota WWTP typically comes from one of two sources: groundwater or surface water. In general, these two source waters will have distinct water chemistries. The natural geology of

Minnesota and the wonders of chemistry cause these two sources of water to diverge in chemical composition.

Groundwater salt sources

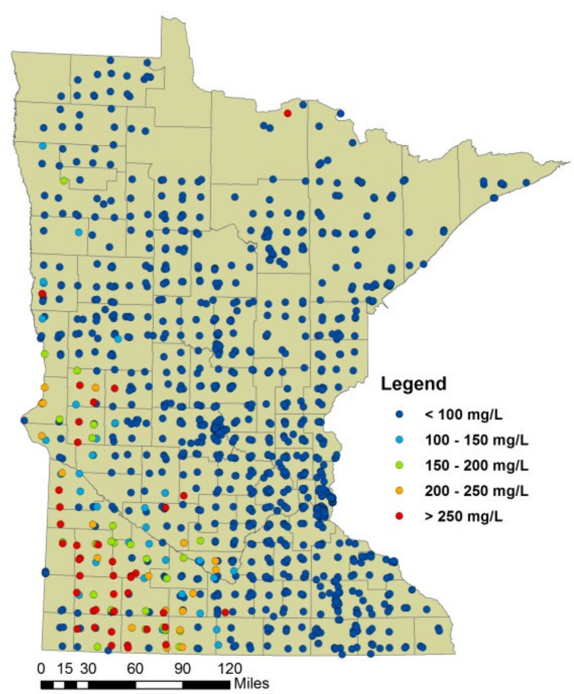
Groundwater exists in the pore spaces of rock in underground aquifers. Except for the northeast part of the state, in Minnesota the underground rock that contains the aquifer's water is composed of forms of calcium-containing minerals such as limestone or gypsum. When water moves through these types of minerals, the water acts as a solvent and dissolves the mineral. This mineral dissolution elevates the concentrations of dissolved salt in the water, causing the water to be "hard" and contain minerals. These groundwater resources tend to naturally have a high hardness and salt content because of this combination of water chemistry and geology (Figure 1).

Figure 1. Hardness concentrations in Minnesota water supply wells.



The quantity of a dissolved salt in a groundwater is in proportion to the chemical composition of the mineral in the aquifer. In general, if the aquifer is composed of minerals with high sulfate, radium, magnesium or alkalinity, then the water in that aquifer will have high sulfate, radium, magnesium or alkalinity. While there are geographic patterns to groundwater salt content in Minnesota, it is best to measure a specific well if needing to know the salt content. Sulfate concentrations in Minnesota groundwater supply are shown in Figure 2.

Figure 2. Sulfate concentrations in Minnesota water supply wells.



All Minnesota aquifers contain minerals with very low chloride concentrations. Consequently, chloride naturally occurs in the single digit mg/L concentrations in Minnesota groundwater even if the water has an elevated hardness or mineral content. As a rule, if a groundwater has elevated chloride concentrations the excess chloride can be attributed to chloride from road salt or another anthropogenic source.

Surface water salt sources

In general, surface water has a lower salt content than groundwater in Minnesota. Surface water here can still have high hardness (>180 mg/L as $CaCO_3$) depending on the region. Like groundwater, there are geographic patterns to surface water salt content in Minnesota, but it is best to measure a specific water body if needing to know the salt content.

Again, like groundwater, Minnesota surface waters naturally have very low chloride concentrations (about < 20 mg/L chloride). As a rule, if a surface water has elevated chloride concentrations, the excess chloride can be attributed to chloride from road salt or another anthropogenic source. It is common in Minnesota to see higher surface water chloride concentrations in the wintertime because of road salt runoff.

Anthropogenic salt loading to WWTPs

According to this MPCA analysis, point-of-entry softeners are the dominant source of salt loading to the typical Minnesota municipal WWTP effluent. The dominant ion from this salt loading is chloride; chloride is a component of TDS. As chloride loadings increase, TDS and specific conductance increase proportionally.

There is no statewide system to track chloride loading from point-of-entry softeners and few cities have done any rigorous investigation of point-of-entry softener chloride loading. However, in every Minnesota city where chloride loading has been tracked – Pipestone, Morris and Alexandria – point -of-entry softeners are the dominant source. Unless there is industrial chloride loading, the dominant chloride source is almost certainly from point-of-entry softeners, especially where the source water has high hardness levels.

The city of Alexandria is one of the few cities in Minnesota to perform a citywide chloride source mass balance to its WWTP. The city found that about 10% of the chloride loading to the WWTP is from source water and is thus not amenable to source reduction. Industrial users produce about 17% of the chloride loading to the WWTP. The balance of 73% is from residential loading with the substantial majority of that chloride loading coming from point-of-entry softeners. Based on MPCA 'back of the envelope' analysis, it is reasonable that point-of-entry water softeners are contributing greater than 500 mg/L of chloride to the effluent of the Alexandria WWTP (Data: ALASD Chloride Management Plan, 2014).

The high chloride loading from point-of-entry water softeners is best thought of using the "tragedy of the commons" analogy. No single point-of-entry ion exchange water softener is individually causing high chloride concentrations in the effluent of a WWTP. However, the aggregate chloride loading from all of the point-of-entry softeners collectively contribute to the high chloride loading at the WWTP.

A mass balance study of chloride sources to WWTPs in Santa Clarita, California, estimated that on average 31 mg/L of chloride are added above baseline chloride concentrations from households not using point-of-entry water softeners. The sources of this chloride are personal care products, washings and other domestic sources. The Santa Clarita study estimated that a point-of-entry water softener added 1.34 lbs/day of salt loading to the WWTP corresponding to an increased chloride concentration above baseline of between 367 to 435 mg/L (2002 and 2014, Santa Clarita study). For lack of better data in Minnesota, it is reasonable to assume that a residence in this state is contributing chloride loading to WWTPs at similar rates to Santa Clarita.

Even with the data available, extrapolating point-of-entry water softener chloride loading from one Minnesota city to the next is a complicated task. In order to understand point-of-entry water softener chloride loading to a Minnesota WWTP, a brief primer of residential water softeners is necessary and is provided below.

Fundamentals of point-of-entry ion exchange water softener chloride loading

- Point-of-entry softeners use ion exchange resins to remove calcium and magnesium hardness from incoming water.
- As hard incoming water passes through the point-of-entry softener ion exchange column, the column eventually becomes saturated and is no longer able to remove calcium and magnesium from the influent water.

- In order to regenerate the resin, a concentrated brine of sodium or potassium chloride is backwashed through the ion exchange resin column to displace all of the calcium and magnesium ions that have accumulated on the resin.
- This highly concentrated chloride containing brine is disposed down the sanitary sewer.
- After the chloride containing brine is disposed down the sanitary sewer, incoming water is routed again through the ion exchange resin to remove hardness.
- The backwash process and disposal of salt brine is repeated as necessary to ensure that the ion exchange resin is never overloaded and always has the capacity to remove hardness from incoming water.

The amount of chloride a point-of-entry softener will load to the WWTP can be characterized generally using the concepts below. As can be seen, the chloride loading from any individual point-of-entry water softener is dependent on many variables and is specific to the individual homeowner's water chemistry, water use, hardness preferences, and softener efficiency.

$$\uparrow Water\ Hardness = \uparrow\ Greater\ Backwash\ Frequency = \uparrow Chloride\ Loading\ to\ WWTP$$

$$\uparrow Home\ Water\ Use = \uparrow\ Greater\ Backwash\ Frequency = \uparrow Chloride\ Loading\ to\ WWTP$$

$$\uparrow Degree\ of\ Desired\ Softening = \uparrow\ Greater\ Backwash\ Frequency = \uparrow Chloride\ Loading\ to\ WWTP$$

$$Poorly\ Optimized\ Backwash\ Frequency = \uparrow\ Greater\ Backwash\ Frequency = \uparrow Chloride\ Loading\ to\ WWTP$$

In general, point-of-entry water softener types can be classified into two broad categories:

- Timed softeners – These are set to regenerate the ion exchange resin on a fixed schedule. These softeners are usually older. They are less salt efficient because they are set to err on the side caution and frequently backwash more often than needed to ensure that soft water is always available to the user.
- Demand softeners – These are set to regenerate the ion exchange resin whenever the capacity of the ion exchange capacity is reached. "Smart" models can be optimized to minimize resin regeneration frequency using a variety of optimization techniques.

A full characterization of Minnesota point-of-entry water softener types and use has not been completed to the knowledge of the MCPA. However, based on conversations with state residents and water resource professionals, a large fraction of Minnesota water softeners are of the timed variety. Demand softeners are increasingly common, but are frequently not fully optimized to minimize backwash frequency and thus chloride loading.

Water softener fouling and resin efficiency

Ion exchange is not a "chloride efficient" way to remove hardness from water. The California Health and Safety Code's salt-efficiency standard is 4,000 grains of hardness as calcium carbonate ($CaCO_3$) removed per 1 pound of sodium chloride (NaCl) loaded to WWTP. This represents a loading of about 1 mg of chloride for every 1 mg of hardness of $CaCO_3$ removed.

It is unlikely that most Minnesota point-of-entry residential water softeners are operated at the ideal target salt efficiency. The California salt-efficiency standard assumes that a new high efficiency water softener is being used that is fully optimized to minimize backwashing and that the resin is operating at its installation level of efficiency. Even "optimized and smart" residential water softeners can put many hundreds of pounds of chloride down the drain over the course of a year.

The ion exchange resin beads are a plastic polymer that will reduce in ion exchange capacity over time. There are many reasons a resin might reduce in efficiency over time and common reasons are highlighted below.

Iron fouling

Any iron present in water coming into an ion exchange resin will reduce chloride efficiency. Iron present in water can reduce the exchange capacity of an ion exchange resin in two ways:

1. Ferrous iron is in a divalent oxidation state and is found dissolved in water. It is frequently called clear iron. Ferrous iron will exchange with sodium on the ion change resin and can be backwashed off the resin by regular resin brine regeneration. Any dissolved ferrous iron will add hardness to the water and increase the frequency of resin regeneration.
2. Ferric hydroxide fouling is a more problematic type of iron fouling. Ferric iron is in a trivalent oxidation state and under normal oxidized conditions will exist as an iron-hydroxide solid commonly called rust. Ferrous iron will oxidize to rust in the presence of oxygen. This rust binds to the ion exchange resin and blocks the ion exchange sites, reducing resin efficiency. This kind of fouling can only be reversed by periodic cleaning using an oxidizing salt approved by the manufacturer. A brine backwash cycle will not fully remove iron hydroxide fouling.

Chlorine and drinking water disinfecting residuals

Chlorine and other associated compounds are strongly oxidizing molecules used to maintain a disinfecting residual in drinking water to protect human health. These oxidizing compounds, when in water, will attack the polymer linkages in the ion exchange resin and over time will degrade the quality of the resin. Manufacturers have done admirable work developing resins that are more resistant to chlorine degradation in recent years but resins that are not exposed to disinfectants will last longer than resins not exposed to disinfectants. Disinfectants will reduce the efficiency of your resin in proportion to the activity of the disinfectant residuals.

The Hellenbrand water treatment company uses the formula below to estimate ion exchange resin replacement interval as a function of free chlorine in the incoming water. The Hellenbrand Company believes that ion exchange resins should be replaced when they have reduced in exchange efficiency by 20%. In Minnesota, most distribution networks run a free chlorine concentration ranging from 0.2 – 1 mg/L representing an average estimated resin replacement interval of 10 to 20 years in the absence of any other resin foulants.

$$Number\ of\ Years\ before\ Resin\ Replacement = \frac{10}{Free\ Chlorine\ (mg/L)}$$

Suspended solids

Ion exchange resins can have an identical function as a sand filter in that they remove particulate solids. However, this is not an efficient use of an ion exchange resin capacity and nearly every manufacturer acknowledges this in their recommended best practices. If present, suspended solids should be removed before the ion exchange resin. Any suspended solids in the incoming water could easily irreversibly foul a membrane resin surface.

A common source of fouling resins is using a low quality rock salt with dirt in it. This dirt will over time foul the resin during backwashing. A pure, high quality salt will increase lifetime resin efficiency.

Bed volume loss

Ion exchange resin beads are made of petroleum byproducts. When these beads are installed, they are round and not cracked. The resin beads can be damaged by the agitation caused by the backwashing process, free chlorine, and water induced osmotic swelling during regeneration. As the beads become damaged, they break into smaller pieces that have a lower mass and higher relative surface area. These small pieces are washed away during the backwashing process and this process overtime results in loss of resin bed volume. As the resin bed volume decreases, the total exchange capacity of the system decreases reducing the chloride efficiency of the water softener.

The Hellenbrand water company estimates that under normal operation a resin bed will lose 1% of its resin volume every year because of resin bead breakdown if the free chlorine concentrations are less than 0.5 mg/L. The bed volume loss can be as high as 3% annually if the resin regenerates frequently and high free chlorine concentrations are present.

Over time, this can cause substantial resin loss and reduce the ion exchange capacity and chloride efficiency of the system. The total bed loss as a percent of original bed volume can be visualized in the table below.

Table 2. Compounded resin bed volume relative to initial bed volume overtime assuming a 1% and 3% volume loss per year.

Year	Bed volume loss (1% Annual loss)	Bed volume loss (3% Annual loss)
1	1.0%	3.0%
2	2.0%	5.9%
3	3.0%	8.7%
4	3.9%	11.5%
5	4.9%	14.1%
6	5.9%	16.7%
7	6.8%	19.2%
8	7.7%	21.6%
9	8.6%	24.0%
10	9.6%	26.3%

Alternative analysis

The MPCA conducted an alternatives analysis to evaluate options that might reduce chloride loading to the WWTP. Broadly, these options fall under three categories:

1. Drinking water source reduction
2. Point-of-entry softener optimization
3. Chloride treatment at the WWTP

These categories were screened by these three questions:

1. Can the alternative produce a chloride loading reduction?
2. Could the alternative individually comply with Minnesota's 230 mg/L chloride standard?
3. What is the feasibility and relative cost of the alternative?

Table 3 outlines the feasibility of the three reduction categories with detailed discussion.

Table 3. Feasibility of the three reduction categories to reduce chloride in wastewater discharges

	Alternative	WWTP chloride reductions possible?	Ability to bring WWTP into chloride compliance	Ability to bring WWTP into other salty parameter compliance?	Technical feasibility	Implementation feasibility	Estimated relative cost
Drinking water source reduction	Centralized lime softening	Yes	Likely*	Likely*	Yes	Feasible	High
	Centralized RO softening	Yes	Likely*	Likely**	Yes	Feasible	High
	Ferric chloride --> Ferric sulfate	Yes	Unlikely	Unlikely	Yes	Feasible	Low
Softeners	Upgrade to high salt efficiency Point-of-entry softeners	Yes	Unlikely	Unlikely	Yes	Feasible	Medium
	Upgrade industry to high efficiency softeners	Yes	Unlikely	Unlikely	Yes	Feasible	Medium
	Outlaw ion exchange point-of-entry water softeners	Yes	Likely	Likely**	Yes	Not Feasible	Medium
	Create softener column exchange and Collection Program	Yes	Likely	Likely**	Yes	Feasible	High
	Switch to non-ion exchange softeners	Yes	Likely	Likely**	No	Feasible	Medium
	Increase residential softening target	Yes	Unlikely	Unlikely	Yes	Not Feasible	Medium
WWTP chloride treatment	RO effluent - Concentrate discharged to surface water	Yes	Likely	Likely	No	Not Feasible	High
	RO effluent - Concentrate crystalized/evaporated	Yes	Likely	Likely	Yes	Not Feasible	Very High
	RO effluent - Concentrate deep well injection	Yes	Likely	Likely	No	Not Feasible	Very High
	Chlorination to UV disinfection	Yes	Unlikely	Unlikely	Yes	Feasible	Medium
	Ferric chloride to ferric sulfate	Yes	Unlikely	Unlikely	Yes	Feasible	Low
	Chloride precipitation with silver nitrate	Yes	Possible	Unlikely	Yes	Not Feasible	Very High
	Chloride anion exchange	Yes	Possible	Unlikely	No	Not Feasible	Very High
	Electrodialysis	Yes	Possible	Unlikely	Yes	Feasible	High
	Any biological treatment process	No	Impossible	Impossible	No	Not Feasible	NA

*If all point-of-entry ion exchange softeners are taken offline. ** If all point-of-entry ion exchange softeners are taken offline and source water quality has concentrations below Classification 3 and 4 water quality salty parameter standards.

Drinking water source reduction

Centralized lime softening and disconnecting point-of-entry softeners

Rationale

Switching a city's drinking water to centralized lime softening and disconnecting point-of-entry softeners is a way to reduce and come into compliance with chloride and Classification 3 and 4 water quality standards at the WWTP through chloride source reduction. The assumptions behind this alternative are outlined below:

- The city switches to a drinking water treatment plant that softens the water using lime softening. Lime softening chemically precipitates hardness, alkalinity and adds no chloride to the treated water. The water is softened to a hardness of < 100 mg/L as CaCO3.
- All of users are connected to both city drinking water and discharge to city sewers.
- Point-of-entry residential softeners are taken off-line because removing hardness at the point-of-entry is no longer necessary. This applies only to locations connected to city water.
- Chloride loading to the WWTP from point-of-entry softening decreases to a level that could comply with the effluent limit based on Minnesota's 230 mg/L chloride standard.
- Salty parameters decrease to a level that could comply with the effluent limit based on the Classification 3 and 4 water quality standards.

Lime softening is a chemical method of removing hardness from a drinking water. It is always employed at a centralized drinking water treatment plant and is infeasible at a residential scale or with a distributed well network.

Lime softening works by adding lime to the water, which raises potential of hydrogen (pH) to greater than 10.3 and initiates precipitation of hardness and alkalinity ions as calcium carbonate. If the water has high levels of magnesium hardness, excess lime softening would be required to increase the pH to approximately 11 and soda ash (Na2CO3) would also be added.

In Minnesota, drinking water is almost always excess lime softened because of high magnesium hardness.

A typical Minnesota groundwater source that has been excess lime softened will have a significantly lower mineral content than water not lime softened due to removal of calcium and magnesium. Lime softening also lowers TDS by precipitation of hardness and alkalinity. As the TDS decrease, specific conductance decreases proportionally, because there is less dissolved mineral content to conduct electricity (Table 4). If sulfate concentrations are low, then the amount of sodium added during excess lime softening through soda ash only contributes marginally to TDS and is insignificant relative to the amount of TDS removed by hardness precipitation (Figure 3).

Figure 3. Major ion content of water that has been excess lime softened and ion exchange softened compared to the untreated source water.

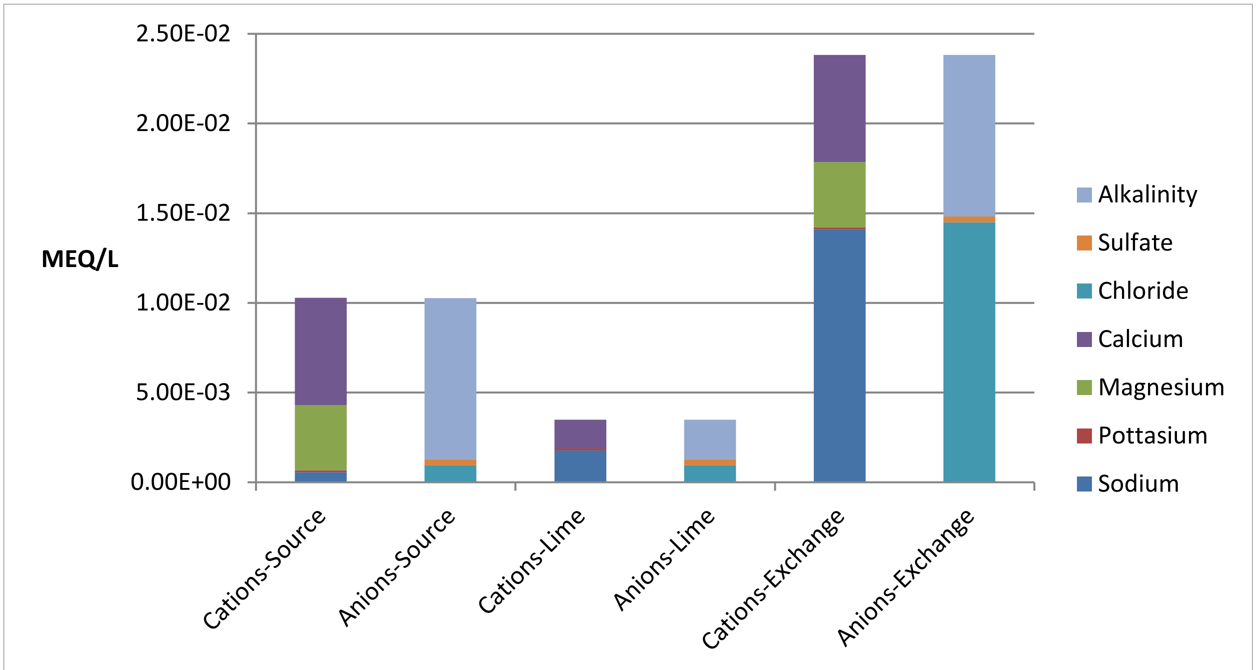


Table 4. Major ion content of water that has been excess lime softened and ion exchange softened compared to the untreated source water from Figure 3. TDS and Specific Conductance are calculated values using equations 1 and 2.

Parameter	Na	K	Mg	Ca	Hardness	Cl	SO_4	Alkalinity	Ionic Strength	TDS	Spec. Cond.
Unit	mg/L	mg/L	mg/L	mg/L	mg/L as CaCO3	mg/L	mg/L	mg/L as CaCO3	mMoles	mg/L	µmho /cm
Source	13.1	4.1	44.1	120	480	33.6	15.7	450.3	14.4	577	901
Excess Lime Softening	40.6	4.1	0.3	32.1	80.8	33.6	15.7	158	4.3	172	269
Ion Exchange Softening	324	4.1	44.1	120	480	514	15.7	450.2	28.0	1121	1751

Equations 1 and 2 are taken from Snoeyink and Jenkins, 1980. They were rearranged to calculate TDS and specific conductance for the modeled water in Table 4.

$$Equation\ 1.\ Ionic\ Strength\ (Moles) = 2.5\ X\ 10^{-5}\ x\ TDS\ (\frac{mg}{L})$$

$$Equation\ 2.\ Ionic\ Strength\ (Moles) = 1.6\ X\ 10^{-5}\ x\ Specific\ Conductance\ (\mu mho/cm)$$

Table 5 shows the general impacts of centrally limed softening and ion exchange softening to source water. These general trends will be true regardless of the specific water chemistry of the source water. Additionally, lime softening can remove gross alpha emitters, heavy metals (Pb, Cr(III), Hg, As), iron and manganese, turbidity, some organic compounds, and control algae, bacteria and viruses. Enhanced lime softening can remove dissolved organic carbon and thus decrease the formation of disinfection byproducts in the chlorination process (MWH, 2005).

Table 5. Effects of the softening strategy on the concentration of the given parameter relative to the source water at the wastewater effluent.

Parameter	Centralized excess lime softening	Point-of-entry ion exchange
Hardness	Decreased	Unchanged
Alkalinity (Bicarbonates)	Decreased	Unchanged
Total dissolved solids	Decreased	Increased
Specific conductance	Decreased	Increased
Chloride	Unchanged	Increased
Sodium	Slight Increase	Substantial increase

This assumes no significant source of the parameter between the drinking water plant and the wastewater plant. At a neutral pH between 7 to 9, greater than 95% of alkalinity is present as bicarbonate, so for the purposes of this memo alkalinity and bicarbonates can be used interchangeably.

If lime softening at the drinking water treatment plant and the full removal of point-of-entry ion exchange softeners is implemented then the wastewater plant would comply with its chloride limits and the Classification 3 and 4 parameters in Table 1. The predicted ranges associated with this treatment alternative can also be found in Table 6. The predicted values in Table 6 assume that there is no significant source of these parameters between the drinking water plant and the wastewater plant. For typical Minnesota drinking water, TDS would be less than 700 mg/L after excess lime softening. However, if the source water has a high absolute concentration of ions that are not removed during softening (Na, Cl, K, SO4) then the predicted concentrations in Table 6 are not valid.

Table 6. Expected levels in a wastewater effluent of the selected parameter if the chloride treatment alternative involving excess lime softening at the drinking water plant is fully implemented.

Parameter	Units	Average range	Water quality standard
Chloride	mg/L	< 230	230 (2B)
Hardness	mg/L as CaCO3	< 500	500 (3B)
Total dissolved solids	mg/L	< 700	700 (4A)
Bicarbonates	mg/L as CaCO3	< 250	250 (4A)
Specific conductance	µmho/cm	< 1,000	1,000 (4A)

When is it necessary to disconnect all point-of-entry water softeners?

Installing centralized lime softening and removing all point-of-entry softeners, has the highest degree of certainty of ensuring compliance with chloride and salty parameter limits.

Making specific assumptions, listed below, it may be possible to reliably meet chloride effluent limits through centralized lime softening while still allowing the use of high efficiency point-of-entry softeners in the distribution network.

- All point-of-entry softeners are rated as having high salt efficiency of at least 4000 grains of hardness per pound of salt.
- All point-of-entry softeners are optimized to minimize salt use.
- The water supplied to households is softened to less than 8 gpg or 137 mg/L as CaCO3.

- There are no significant sources of chloride (chlorine, SIUs, road salt intrusion, source water, etc…) that could cumulatively contribute to a violation of chloride limits when high efficiency point-of-entry softeners chloride loading is also included.

The MPCA recommends that a numeric evaluation of all potential chloride sources be completed before a municipality commits to recommending the use of high efficiency point-of-entry water softeners in the wastewater collection network. Evaluating the information provided in the "upgrading to high-efficiency softeners" section of this report could also be useful.

Feasibility

This option has the potential to reduce chloride loading to the WWTP. This option also has the potential to meet the chloride limits because it eliminates chloride loading from point-of-entry water softeners. A reduction in chloride concentrations in the WWTP effluent that complies with permit limits is theoretically possible. Every city that fully implemented this alternative could comply with the chloride water quality standard.

This option is technically feasible.

However, this option has some significant feasibility concerns:

- The city would need to develop the political will to finance, design, and construct a lime softening drinking water plant.
- All or a large majority of city residents and businesses would need to connect to a drinking water distribution network. For cities with no water distribution network, this represents significant challenges for customers adjusting to new systems and cities building the infrastructure.
- The city would need to establish the authority to create rules, incentives, and inspections to eliminate and verify the elimination of point-of-entry water softener use.
- Typically, drinking water treatment plants do not soften down to less than one grain of hardness like many point-of-entry softeners. Typically, lime softened water has a target hardness of four to five grains of hardness. Residents who point-of-entry soften to one grain of hardness or less would need to adjust to water with increased hardness levels. While the water may feel different, four to five grains of hardness is acceptable for most boilers and lathering concerns.
- Industrial users receiving city drinking water would need to evaluate whether softened waters work with their industrial processes.
- Source waters with high sulfate concentrations limit the TDS endpoint that is possible using lime softening. Lime softening might not be feasible for high sulfate waters as a means to reduce TDS.
- Lime sludge storage and disposal plans would need to be managed.

Cost

Bolton and Menk provided estimates for the costs of building treatment plants to soften water with lime, and for total operation and maintenance (Figures 4 and 5). The costs assume a 10-hour working day for the operators and sludge thickening of the lime solids. The costs in Figure 5 incorporate the costs of a 20-year pay back schedule for the capital costs with a 4% interest rate and an O&M cost of $7/1,000 gallons of water produced.

Figure 4. New lime softening drinking water plant capital costs by population size.

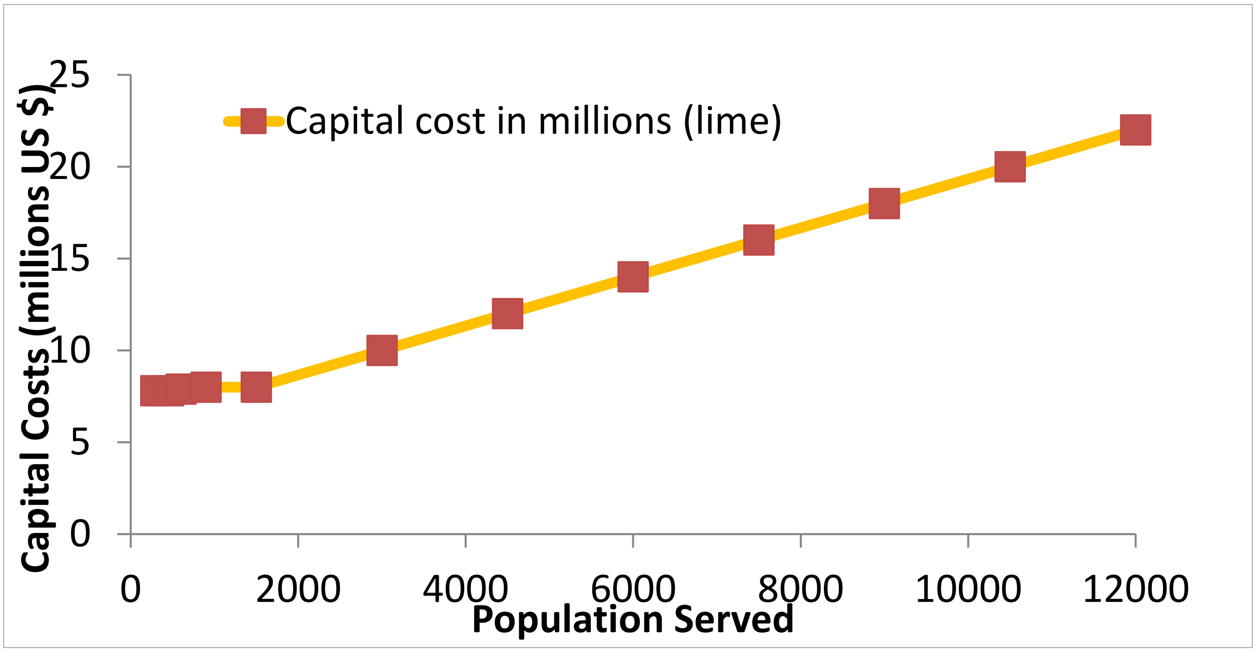
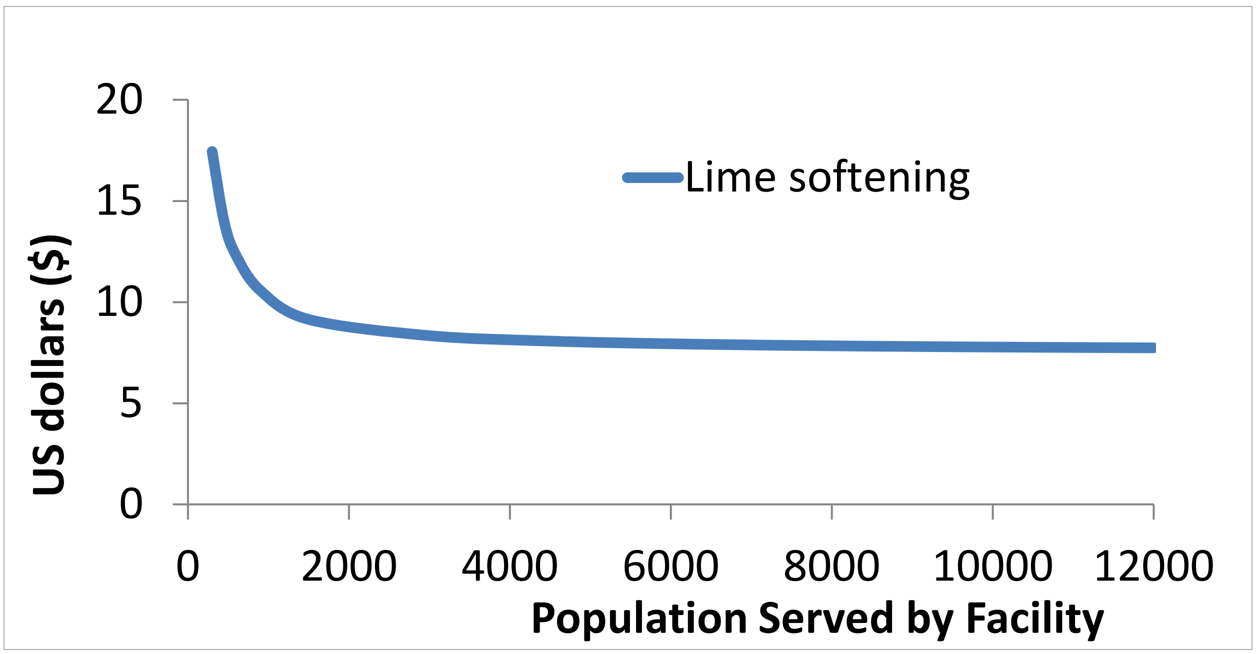


Figure 5. Annualized lime softening drinking water plant costs (capital and O&M) by population size.



These costs represent an initial estimate for new lime softening plants. Costs for lime softening plants depend greatly on the source water quality among a myriad of other factors. It is unlikely that other communities could build lime-softening plants for significantly less than these numbers. If the water has a high sulfate content (ienon-carbonate hardness) then the O&M costs could be even higher than in Figure 5, because higher amounts of soda ash could be required and soda ash is at least two times more expensive than lime.

Centralized lime softening can be a cost effective way for residents to softener their water compared to point-of-entry softening. The city of Bloomington, Minnesota, has centralized softening and has performed an analysis for users that shows that a point-of-entry user can save up to $30 a month on their drinking water costs through centralized softening compared to point-of-entry water softening. When factoring in the costs of a typical point-of-entry water softener including purchase, installation, operation and maintenance, centralized softening saved Bloomington users about $1.21/1,000 gallons of water (Personal Communication, Steve Roepke, City of Bloomington).

The costs of installing a drinking water distribution network, connecting residents to city drinking water or disconnecting point-of-entry water softeners are not considered in this analysis because they are specific to each individual city. Nevertheless, these costs are non-trivial and would be expensive.

Centralized reverse osmosis softening and disconnecting point-of-entry softeners

Rationale

Switching a city's drinking water to centralized RO softening and disconnecting point-of-entry water softeners is a way to reduce chloride and comply with chloride standards at the WWTP. The assumptions behind this alternative include:

- The city switches to a drinking water treatment plant that softens the water using RO. Reverse osmosis physically removes hardness and adds no chloride to the water.
- All or a substantial fraction of users are connected to both city drinking water and discharge to city sewers.
- Point-of-entry residential softeners are taken off-line because hardness removal at the point-of-entry is no longer necessary. This applies only to locations connected to city water.
- Chloride loading to the WWTP from residential users is reduced to a level that could comply with the effluent limit based on the 230 mg/L chloride standard.
- If the source water has concentrations of Classification 4 parameters below the applicable water quality standards, then the facility will potentially comply with potential Classification 3 and 4 limits.

Feasibility

This option has the potential to reduce chloride and TDS loading to the WWTP. This option has the ability to meet Classification 3 and 4 limits if the source water has TDS, hardness and alkalinity concentrations below the Classification 3 and 4 water quality standards.

RO softening does not reduce the salt loading a WWTP would receive relative to the source water. RO softening works by reducing the salt loading the end-users receive and routing the concentrated salt mass to the WWTP. Figure 6 demonstrates how flow and salt mass is routed using centralized RO softening. If the water supply has salt concentrations that are above Classification 3 and 4 water quality standards, then this option would not be able to guarantee compliance with a Classification 3 and 4 limit at the WWTP (Table 7).

Q = Flow; Ch = Concentration of Hardness; Mh = Mass rate of Hardness; Ccl = Concentration of Chloride;

Mcl = Mass rate of Chloride

Figure 6. How RO softening could guarantee compliance with chloride limits but not hardness limits if the source water has high hardness values.

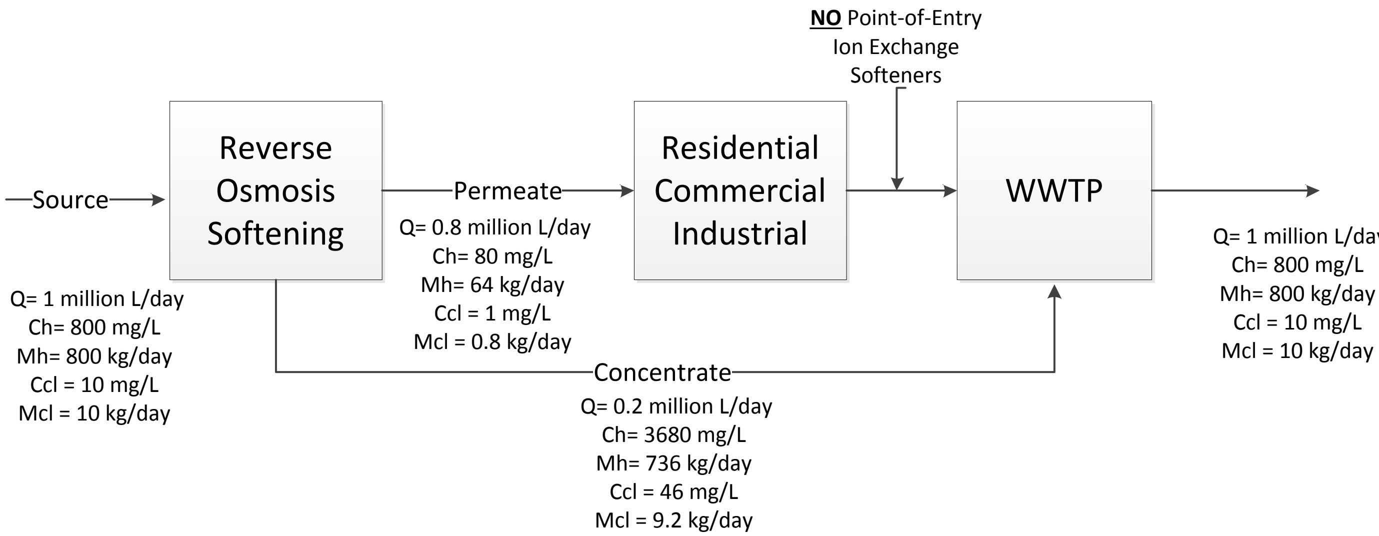


Table 7. Reasonable potential for a given parameter using RO softening and eliminating IX softeners if the source water also has RP.

Parameter	Source water RP	RP at WWTP using centralized RO softening and eliminating IX softeners
Chloride	No	No
TDS	Yes	Yes
Specific Conductance	Yes	Yes
Hardness	Yes	Yes
Alkalinity	Yes	Yes

This option also has the potential to be able to meet the chloride limits because it eliminates chloride loading from point-of-entry water softeners. A reduction in chloride concentrations in the effluent of the WWTP greater than 350 mg/L is theoretically possible in some locations.

This option is technically feasible.

However, this option has some significant implementation concerns highlighted below:

- The city would need to develop the political will to finance, design, and construct an RO drinking water plant.
- All or a large majority of city residents and businesses would need to connect to a drinking water distribution network. For cities with no water distribution network, this represents significant challenges for customers adjusting to new systems and cities building the infrastructure.
- The city would need to establish the authority to create rules, incentives, and inspections to eliminate point-of-entry water softener use.

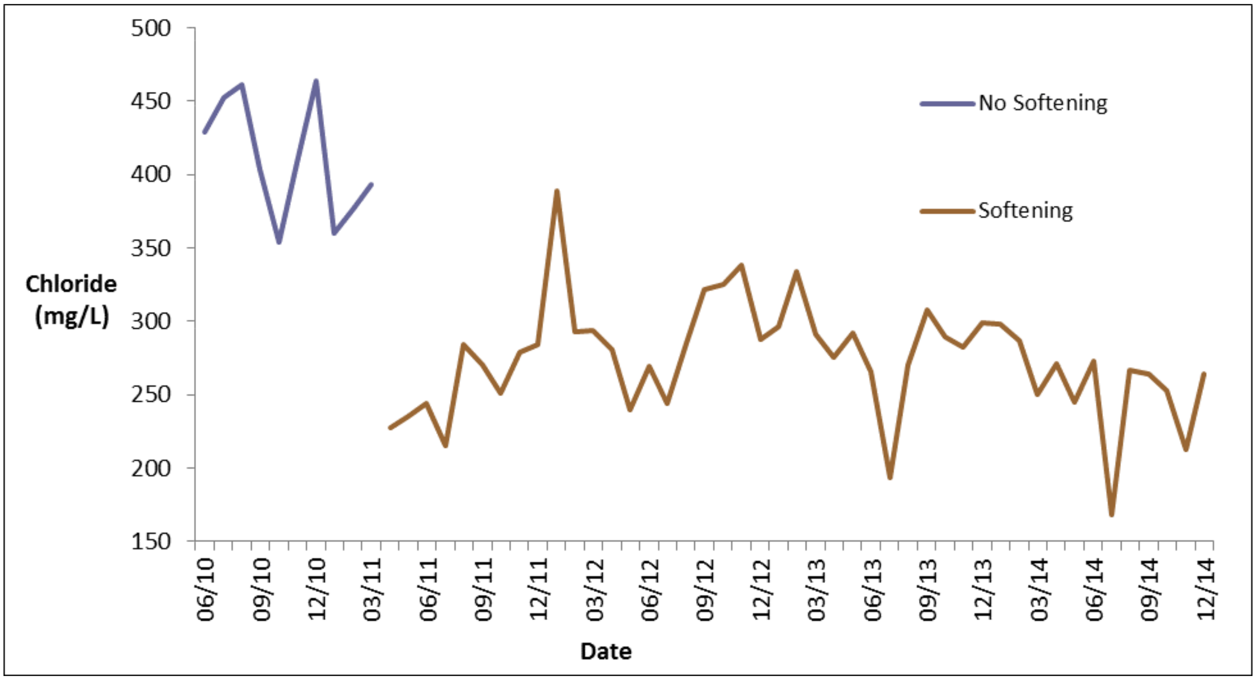
- Typically, drinking water treatment plants do not soften down to less than one grain of hardness like many point-of-entry softeners. Typically, lime softened water has a target hardness of four to five grains of hardness. Residents who point-of-entry soften to one grain of hardness or less would need to adjust to water with increased hardness levels. While the water may feel different, four to five grains of hardness is acceptable for most boilers and lathering concerns.
- Industrial users receiving city drinking water would need to evaluate whether softened waters work with their industrial processes.
- The city would need to find a way to manage the RO concentrate stream. An RO concentrate stream has highly concentrated salt concentrations that are notorious for failing toxicity tests and “salty” discharge limits when discharged directly to Minnesota surface water. Some cities will be able to send RO reject to the WWTP if the WWTP has a high assimilative capacity with respect to the receiving water.
- A RO plant is less water efficient compared to a lime softening plant. Typically, about 20 to 25% of the water being RO treated is wasted as concentrate not fit for consumption.

This option has been implemented at the St. Peter, Minnesota, WWTP and has successfully reduced effluent chloride to concentrations that are close to complying with an effluent limit based on 230 mg/L chloride standard in the absence of available stream dilution. The St. Peter WWTP does not have chloride limits in its current permit because it discharges directly to the Minnesota River, which has a high assimilative capacity for dilution.

In March of 2011, the city of St. Peter initiated operations of a drinking water RO softening plant. City residents were notified that they no longer needed to soften their water to the same degree as before. City residents are still allowed to operate point-of-entry water softeners; the city has no metrics that track water softener use before and after the RO plant initiated operation.

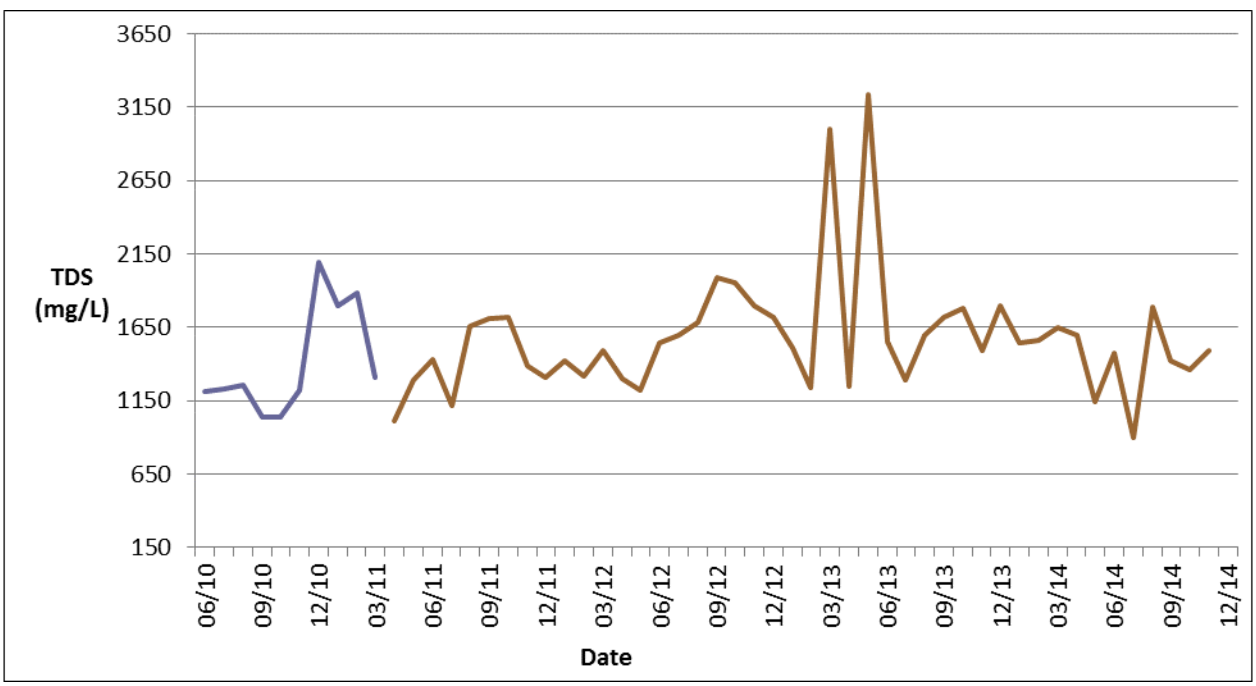
There is a significant difference in effluent chloride concentrations from the WWTP from before and after the RO plant initiated operation (Figure 7). An average chloride reduction of 136 mg/L was achieved after the RO plant was initiated. There is a non-significant trend of effluent chloride concentrations decreasing from 2013 to 2014; it is possible that further reductions in effluent chloride concentrations could be expected as more residents take their point-of-entry water softeners off line. The WWTP currently has no limits for any salty parameters and will not receive any in their new permit issuance they discharge to the Minnesota River where there is ample stream dilution available.

Figure 7. Effluent chloride concentrations at the St. Peter WWTP before and after RO softening at the drinking water treatment plant.



It should be noted that the St. Peter WWTP receives the RO concentrate from the drinking water treatment plant. There has been no significant difference in the effluent TDS concentration at the WWTP before and after initiation of the RO plant (Figure 8). This suggests that the reductions in chloride loading from point-of-entry water softeners has been balanced by the increase in total salt loading from

Figure 8. Effluent TDS concentrations at the St. Peter WWTP before and after RO softening at the drinking water treatment plant.



the RO concentrate stream. A RO concentrate stream has elevated levels of total dissolved salts because the total salt load in the influent water is concentrated into approximately 25% of the influent flow.

When is it necessary to disconnect all point-of-entry water softeners?

Installing centralized RO softening and removing all point-of-entry softeners, has the highest degree of certainty of ensuring compliance with chloride and salty parameter limits.

Making specific assumptions, listed below, it may be possible to reliably meet chloride effluent limits through centralized RO softening while still allowing the use of high efficiency point-of-entry softeners in the distribution network.

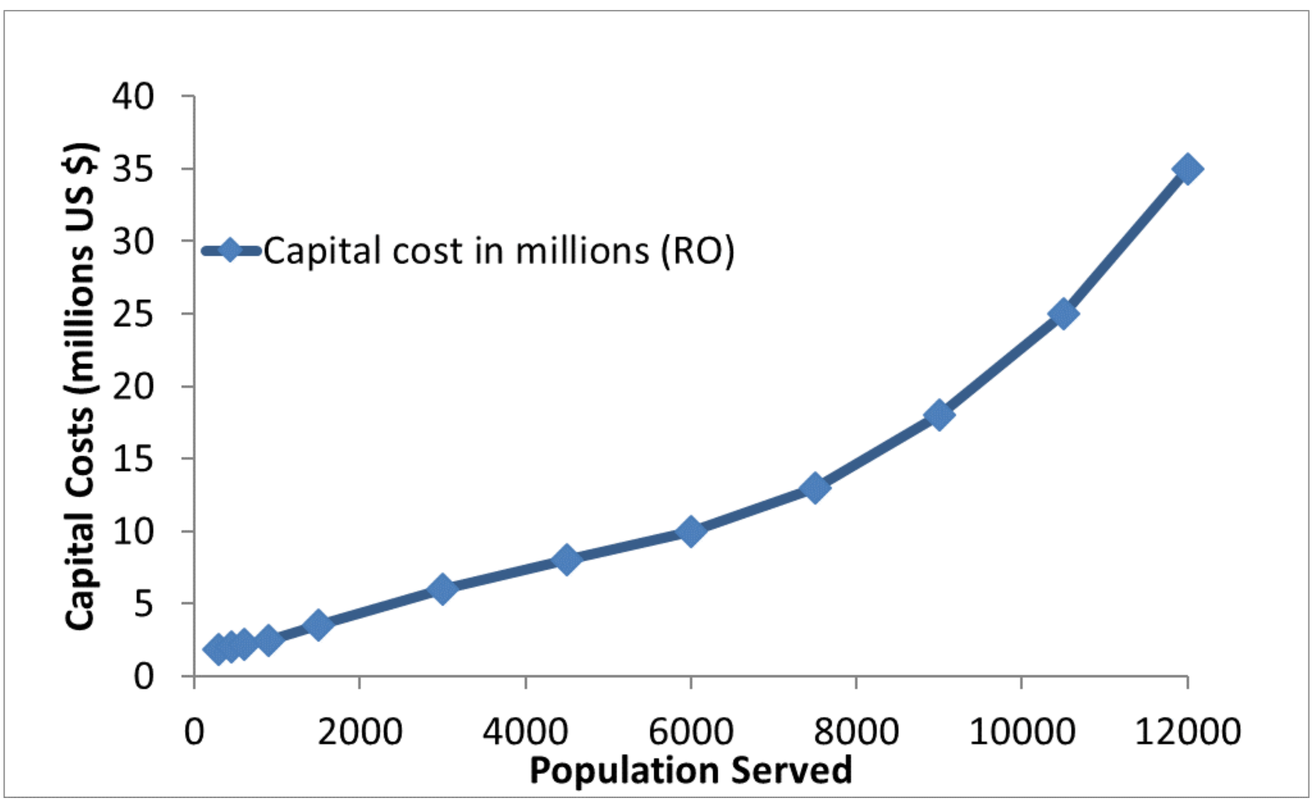
- All point-of-entry softeners are rated as having high salt efficiency of at least 4000 grains of hardness per pound of salt.
- All point-of-entry softeners are optimized to minimize salt use.
- The water supplied to households is softened to less than 8 gpg or 137 mg/L as $CaCO_3$.
- There are no significant sources of chloride (chlorine, SIUs, road salt intrusion, source water, etc…) that could cumulatively contribute to a violation of chloride limits when high efficiency point-of-entry softeners chloride loading is also included.

The MPCA recommends that an evaluation of all potential chloride sources be completed before a municipality commits to recommending the use of high efficiency point-of-entry water softeners in the wastewater collection network. Evaluating the information provided in the “upgrading to high-efficiency softeners” section of this report could also be useful.

Cost

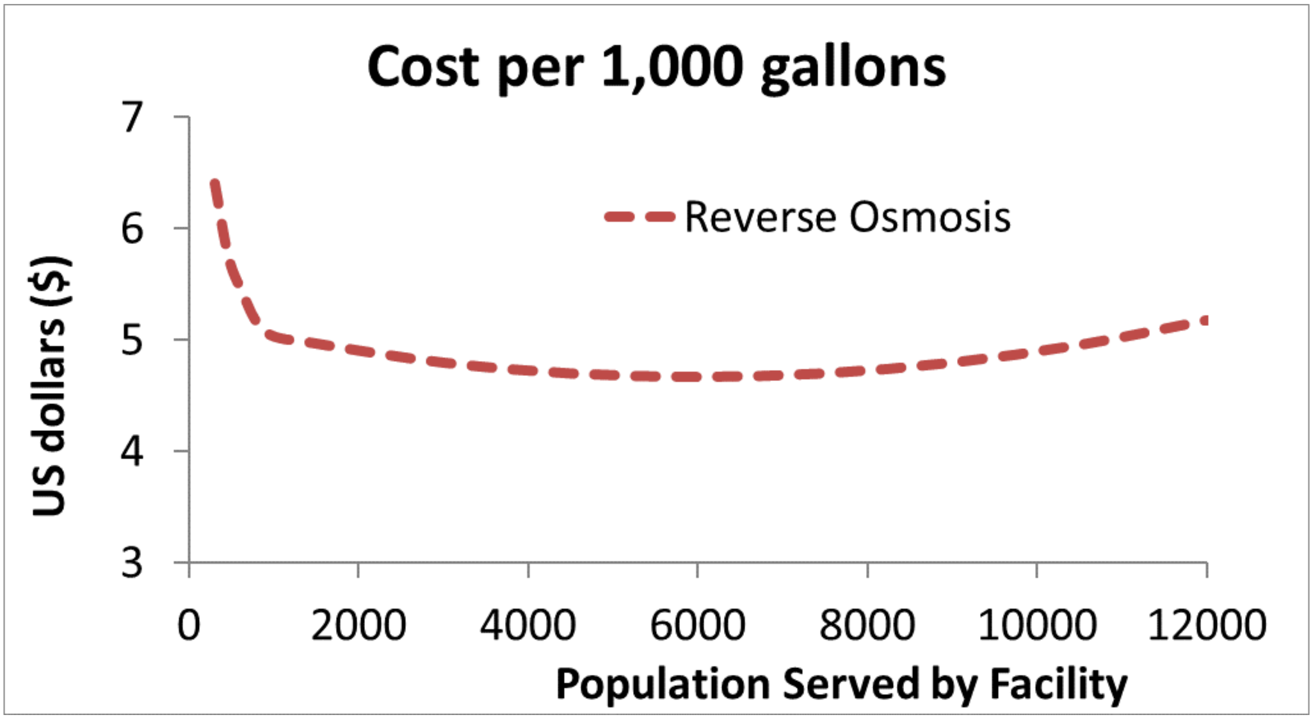
Bolton and Menk provided the MPCA cost estimates for new RO softening water treatment plants capital and O&M costs in the Figures 9 and 10 that follow. The costs in the Figure 10 incorporate the

Figure 9. New RO softening drinking water plant capital costs by population size.



costs of a 20-year pay back schedule for the capital costs with a 4% interest rate and an O&M cost of $4/1,000 gallons of water produced.

Figure 10. Annualized RO softening drinking water plant costs (capital and O&M) by population size.



These costs represent an initial best guess for new RO softening plants. Costs for RO softening plants are very dependent on the source water quality among a myriad of other factors. It is unlikely that other communities would be able to build RO softening plants for significantly less than these numbers.

RO can be a cost-effective way for small communities to centrally soften their water. RO treatment can be automated in a way that lime softening cannot be and because of this less operator work and skill requirements is required for RO treatment.

Switching from chloride-containing additives to additives without chloride

Rationale

Drinking water treatment plants frequently use additives such as ferric chloride or aluminum chloride hydroxide as coagulants in their treatment systems. If a drinking water plant were to switch to an additive such as ferric sulfate or alum that do not contain chloride, then chloride loading to the WWTP would ultimately be reduced.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

This option does not have the potential for a WWTP to meet its chloride limit. A reduction in chloride concentrations in the WWTP effluent of less than 25 mg/L is theoretically possible, assuming the drinking water plant uses additives that contain chloride and switches to a chloride free additive.

This option is technically feasible. Switching to coagulants that do not contain chlorides is feasible for many coagulants. The non-chloride containing versions of these additives are often similar in function and cost.

Chlorination must remain as an option for disinfection for drinking water treatment plants. Chlorinating drinking water is a public health necessity. Alternatives for chlorine disinfection at a drinking water treatment plant are not considered in this analysis.

Cost

Switching to chloride free versions of certain chemicals is a cost-effective option because many of the non-chloride versions are cost competitive compared to the chloride containing version and could be dosed using the same equipment.

Upgrade to high salt-efficiency residential softeners

Rationale

As mentioned in the background section of this document, residential ion exchange softeners can be broadly classified into two categories:

- Timed softeners – These are set to regenerate the ion exchange resin on a fixed schedule. These softeners are usually older. They are less salt efficient because they are set to err on the side caution and frequently backwash more often than needed to ensure that soft water is always available to the user.
- Demand softeners – These are set to regenerate the ion exchange resin whenever the capacity of the ion exchange capacity is reached. “Smart” models can be optimized to minimize resin regeneration frequency using a variety of optimization techniques.

New ‘smart’ water softeners are sold by many manufacturers. The smartest of these models use automated process controls that continuously monitor the water and automate backwashing in order to minimize salt loading to the WWTP. There are many brands in Minnesota that sell water softeners with high salt-efficiency ratings greater than 4,000 grains of hardness as $CaCO_3$ / 1 lb NaCl. An optimized demand softener could be about 40-50% more salt efficient than a poorly optimized timed softener (ALASD, 2014; Lake et al., 2015).

If a resident were to uninstall an old timed softener and replace it with a new optimized demand softener, there would be a reduction in the chloride loading to the WWTP. A new demand softener could be optimized to minimize backwashing and the newer model would have a more efficient ion exchange resin.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

This option has the potential for a WWTP to meet its chloride limit as an individual alternative. However, the WWTP effluent chloride must be with an “attainable margin” to the limit on chloride effluent.

The MPCA operationally uses the following definition of “attainable margin”.

- Measured maximum effluent chloride concentrations are within 100mg/L of the predicted monthly average chloride effluent limit.
- Measured average effluent chloride concentrations are within 50 mg/L of the predicted monthly average chloride effluent limit.

“Attainable margin” means that the required effluent chloride reductions are small enough improving the efficiency of point-of-entry softeners in the distribution network could ensure compliance with final chloride effluent limits. The “attainable margin” definition above is a best professional judgement based on evaluation of cities who have attempted to meet their chloride limits using high-efficiency softeners and point-of-entry chloride loading modeling. A facility may also be within the attainable margin if it has specific documented plans that demonstrate effluent limits could be met through chloride source reduction.

Most WWTPs with chloride limits are discharging chloride concentrations well above effluent limits based on the 230 mg/L standard. For these facilities, it is unlikely that upgrading residences to high-efficiency water softeners will reduce chloride loading by the required amount to guarantee consistent compliance with the chloride water quality standard.

It is possible to make high-efficiency ion exchange softeners look feasible on paper in terms of reducing chloride loading to the WWTP. However, these calculations become less feasible if factoring in a more conservative chloride efficiency rating along with the necessary requirements for ion exchange softeners to be replaced, optimized and maintained.

For facilities averaging chloride concentrations within the “attainable margin” of their chloride limit, it would be worth evaluating the viability of upgrading residences to high-efficiency softeners. It is unlikely that any individual community could attain consistent compliance with just high efficiency softeners. If evaluating this option, a community would need to examine every pro and con, and have a professional engineer review and sign off on the evaluation.

This option is technically feasible.

This option has some implementation concerns:

- As mentioned in the background section, ion exchange is not a chloride efficient way to remove hardness from water. A water softener salt efficiency target of 4,000 grains of hardness as $CaCO_3$ removed/1 pound of NaCl loaded to WWTP represents a loading of about 1 mg of chloride for every 1 mg of hardness as $CaCO_3$ removed.
- Many cities across the United States have grappled with whether high efficiency demand type softeners could help a WWTP come into compliance with chloride limits. A summary of their experiences is provided below.

Alexandria Area Lake Sanitary District (ALASD), Minnesota
One of the most relevant chloride studies to Minnesota is one for ALASD by Wenck Associates as part of its chloride management plan. The study looked at the scenario where all point-of-entry water softeners use a high-efficiency demand based system that minimizes chloride loading to the WWTP. According to the Alexandria chloride management plan, “It became abundantly clear that moving to demand softeners alone would not meet the current permit limit of 252 mg/L (chloride).” The 252 mg/L chloride limit is the WWTP permit limit that would comply with the 230 mg/L water quality standard on a monthly basis.

Personal communications with ALASD indicates that it has examined how upgrading residences to high-efficiency softeners could reduce chloride loading at its WWTP outfall. ALASD reports that high-efficiency softeners could theoretically reduce chloride loading by about 46%, but that the actual reductions would likely be closer to 20% because perpetual maximum softener efficiency is not likely over time. Another contributing factor is that high iron levels in the residences’ source water adds about six grains per gallon of hardness to their water and consequently requires higher backwashing frequency.

The city and its consultants said the city could not come into compliance with its chloride limit by only upgrading to high-efficiency softeners. The main reason for this is because only 70% of the residential wastewater users are connected to city drinking water. The rest have their own private drinking water wells and use softeners to treat their water at the point-of-entry. The typical private well in the Alexandria area has high hardness (36 grams per gallon), and even with a high efficiency softener, treating water that hard using ion exchange sends prohibitively high chloride loads to the WWTP. It would be prohibitively expensive to connect the 30% of users to the drinking water distribution network because they are diffusely located near the edge of city limits.

Santa Clarita, California

The Santa Clarita, California, WWTP has a restrictive 100 mg/L chloride limit. In order to comply with this limit, since 2002 the plant has performed a yearly chloride source evaluation to identify where chloride loading could be reduced. As a result of these studies, the city provided incentives to its residents to install high-efficiency softeners as a way to reduce chloride loading. Residents also received incentives to remove their point-of-entry water softeners. Hundreds of high efficiency water softeners were installed or removed throughout the city as part of this program.

Ultimately, the incentives to replace inefficient point-of-entry water softeners did not reduce chloride loading to the extent required to meet the 100 mg/L chloride limit at the WWTP. The city enacted and began enforcing a ban on point-of-entry residential softeners in 2008 coupled with a softener buy-back program.

Under the current chloride water quality standard (230 mg/L), Minnesota cities would not have to reduce chloride loading to the extent of Santa Clarita (100 mg/L). Nevertheless, there are important findings from the Santa Clarita water softener reduction effort:

- California sanitary district engineers have expressed strongly that they wish they had never initiated a program to install high-efficiency water softeners. Installing high-efficiency water softeners created the public perception that the chloride problem was solved, and when the city took the additional step to outlaw point-of-entry water softeners, there was much public ill will.
- A system of softener laws, supported by the California Legislature, was required to be enacted, enforced, and funded. The city actively seeks out and inspects homes they suspect of having point-of-entry water softeners installed and levels fines up to $1,000 for those in violation.
- Enacting this ban required the city to interact with vendors that sold water softeners to prevent their sale and compensating all water softener rental companies for water softeners installed in residents' homes.

Lake Geneva, Wisconsin

The Lake Geneva, Wisconsin, WWTP has a 250 mg/L chloride limit and discharges to an infiltration basin. The compliance point for the 250 mg/L chloride limit is groundwater monitoring wells downgradient of their infiltration basin. The city is sporadically not in compliance with its chloride limit. The infiltration basin receives stormwater from a nearby highway and consequently the infiltration basin receives chloride loading from both the WWTP and road salt.

The city has a majority of homeowners using point-of-entry water softeners. The city has performed numerous studies and for various reasons has been unable to determine the exact chloride loading from the WWTP to its compliance points because of the difficulties in estimating chloride loading from road salt and inflow and infiltration.

The city has partnered with Culligan to incentivize residents to upgrade to high-efficiency water softeners. According to the city engineer, this has reduced chloride loading to the WWTP, but this is difficult to measure because of high inflow and infiltration (Dan Winkler P.E., Lake Geneva City Engineer, personal communication). The city has also implemented chloride limits on hauled septage to their WWTP that have been effective in reducing chloride loading.

As mentioned above, it is difficult to say exactly how much chloride reduction occurred by switching residents to high-efficiency softeners. It is apparent that switching residents to high-efficiency softeners did not immediately and drastically improve the Lake Geneva WWTP chloride problem.

Madison, Wisconsin

The WWTP for the city of Madison, Wisconsin, has a chloride limit of 395 mg/L and is not in compliance with that limit, typically discharging in the low 400 mg/L chloride. The WWTP currently has a variance from its chloride standard and is striving for compliance with its final permit limit. The city has committed to a strategy of upgrading high-efficiency softeners as a way to comply with its chloride limit.

Madison receives about 57% of its chloride load from residential water softeners, estimating about 101,000 residential water softeners discharge to the WWTP. The city has a distributed drinking water well network, so lime softening at each of its 22 wellheads is much less feasible than in a city with a more centralized drinking water treatment plant.

The city receives a portion of its chloride load from road salt infiltrating into the wellhead protection area. The city is attempting to minimize this load by optimizing road salt application next to wellhead protection areas.

The city has released a report detailing its efforts to determine if upgrading to high-efficiency point-of-entry water softeners could help meet its chloride limit. The study was able to secure funds to either professionally optimize the currently installed softener or upgrade to a new high-efficiency softener. The study then measured chloride loadings from the softeners and found that on average:

- Optimizing the current soften reduced chloride loading by 28%
- Installing new softeners reduced chloride loadings by 46%

The 46% average reduction in chloride loading from new high-efficiency water softeners is a large number that should be used with caution when applied to other cities. The 95% confidence uncertainty intervals associated with that 46% range from 13% to 80%. The large uncertainty intervals result from the wide variation in efficiency and potential chloride reductions from any single softener. An old, poorly optimized timer-based softener might have a loading reduction closer to 80% while there might only be marginal reductions from upgrading a newer well-maintained softener. Also, if the city was able to achieve a 46% reduction in loading from residential water softeners, that would only represent an approximate 26%-reduction in their total chloride load. At that rate, Madison would still not be in compliance with permit limits.

The 46% average reduction in chloride was measured within several weeks of installation after a professional optimization. It is unlikely that the softeners would still operate at their initial efficiency after 5 to 10 years.

The softener optimization study highlights some important suggestions that could possibly further reduce chloride loading from commercial and industrial users. These are not detailed here but could generally be categorized as installation and plumbing improvements for major users.

Costs

The city of Bloomington, Minnesota, estimates that it costs $4.70 to soften 1,000 gallons of water at home, including the costs of operating, installing, and maintaining a point-of-entry water softener. Bloomington estimates it costs an additional $1.21/1,000 gallons to soften at point-of-entry compared to at the drinking water treatment plant. This represents a total monthly cost per household of $35.28, assuming a per household monthly water use of 7,500 gallons. According to the analysis, a resident would expect to save about $30 a month in water treatment costs by using centralized lime softening instead of point-of-entry softening.

A new high-efficiency water softener costs about $500-$1,000 without the costs of delivery and installation. An analysis conducted by the WaterReuse Research Foundation estimates that the 10-year life cycle cost of an ion exchange water softener is $3,500 for water with 150 mg/L hardness.

Upgrade industries to high efficiency softeners

Rationale

There are industrial practices, including upgrading water softeners, which can reduce chloride loading to the WWTP.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

However, this option does not have the potential for a WWTP to meet its chloride limit, unless:

- The facility is already close to the 230 mg/L chloride standard
- Industries discharge significant chloride loading
- Industrial users use technologies that are amenable to chloride reduction strategies

This option is technically feasible for industrial users. These technologies are not feasible for home point-of-entry users because high capital costs are cost-prohibitive.

Some of the feasible implementation strategies include:

- Switching to ion exchange softeners that use a brine reclaim process
- Implementing electrostatic precipitation descaling technologies that can eliminate the need for water softening
- Switching to a dual tank ion exchange column

Cost

These options have been shown to be feasible for industrial users in Madison, Wisconsin, and have shown paybacks of one year (Kathy Lake, Madison Sewer District, personal communication).

Outlaw ion exchange point-of-entry water softeners

Rationale

If a city were to ban point-of-entry water softeners, then they would not be in operation and no chloride would be backwashed to the WWTP.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

This option has the potential for a WWTP to meet its chloride limit.

This option is technically feasible.

However, this option poses some serious implementation concerns:

- Residents would abruptly have no option to reduce hardness in their water. Hardness in some Minnesota cities can be extremely high (>500 mg/L as $CaCO_3$) and this poses problems for boilers, water heaters, and aesthetic concerns.
- The city would need to establish the authority to create rules, incentives, and inspections to eliminate point-of-entry water softener use.

Cost

- The city would need to determine how to address residents' financial loss from the impact of harder water and money invested in softeners.
- The city of Santa Clarita, California, offered rebates of $500- $2,000 per household to compensate for ion exchange softeners that could no longer be used. These numbers seem reasonable for Minnesota.

Create softener column collection and exchange program

Rationale

With a softener column collection program, residents bring their water softeners to a centralized location to be recharged. There would be no need for water softeners to be backwashed in homes. The brine used to recharge these softeners could be reclaimed at the collection center and not discharged to the WWTP.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

This option has the potential for a WWTP to comply with the 230 mg/L chloride standard assuming:

- All residential ion exchange softeners are collected and re-charged at a centralized treatment location.
- This centralized treatment location does not discharge chloride to the WWTP.
- The centralized treatment location would need to find a sustainable political and economic model.
- There are businesses in Minnesota that operate ion exchange water softener collection programs. It is unclear how the business would reclaim the brine.
- This option is technically feasible assuming that the centralized treatment center is able to treat recharge brine and manage the residual sodium and chloride.

Cost

This is the least certain alternative to assign a cost because of the uncertainties as to who would pay the costs of point-of-entry softening and what kind of treatment would be required at the centralized treatment location to deal with the brine.

It is safe to say that this option would be significantly more expensive than operating a residential point-of-entry water softener as they are currently operated.

Switch residents to non-ion exchange softeners

Rationale

If residents used a softening technology that did not use ion exchange, then there would be no need to backwash the ion exchange resin and no chloride loading to the WWTP.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

This option has the potential for a WWTP to meet its chloride limit.

This option is technically feasible for some treatment alternatives. The technical feasibility of each treatment alternative is summarized below from the WaterReuse Research Foundation report, "Evaluation of Alternatives to Domestic Ion Exchange Water Softeners."

Template Assisted Crystallization (TAC)

This technology works by using specially coated plastic beads that form colloidal scale calcium carbonate crystals. After passing through the TAC beads, the calcium that was previously dissolved in the water is transformed into a solid phase microscopic colloidal calcium carbonate crystal, decreasing the free calcium concentration. When the free calcium concentration decreases, the scaling potential is decreased and surfactants perform better. This technology is not typically used at a treatment plant scale and available units are intended for residential use.

Advantages:

- Passive system that doesn't require chemical use or electricity
- Reduces scale formation by >90% and increased detergent effectiveness
- Uses no salt and adds no sodium to water
- No "slimy" water as with ion exchange systems

Disadvantages:

- No dissolved iron, dissolved manganese, phosphates or hydrogen sulfide can be present in the water before treatment
- Not a widespread technology in Minnesota
- Doesn't remove hardness, just transforms it temporarily to a benign solid form that is safe for human consumption
- Can only reduce free calcium concentrations to the solubility product of calcium carbonate

Electrically induced precipitation

This technology works by precipitating calcium carbonate using an electric field. The calcium carbonate precipitate forms on an electrode. The electromagnetic field also causes particles to precipitate that form nucleation sites for further precipitation.

Advantages:

- Reduced scaling by about 50% in test cases
- Produces a soft scale that can be easily removed

Disadvantages:

- Requires electricity year round
- Not a widespread technology

Magnetic water treatment

This technology uses an electric field to change the solid calcium carbonate physical adhesion properties.

Advantages:

- Reduced scaling by about 50% in test cases
- Produces a soft scale that can be easily removed

Disadvantages:

- Requires electricity year round
- Not a widespread technology
- If iron, dissolved oxygen or dissolved silica is present, effectiveness is reduced
- Works best under continuous pipe-full flow conditions
- Substantial body of peer-reviewed literature showing this option is ineffective

Capacitive deionization
This treatment technology uses charged electrodes to adsorb charged ions in the water.

Advantages:

- Removes almost all hardness including other anions

Disadvantages:

- The unit must be regularly backwashed and the polarity of the electrodes must be reversed in order to clean
- Requires electricity
- Not a widespread technology in Minnesota and residential technology is still being developed

Water conditioners
This technology works by adding a chemical to the water that inhibits or controls calcium carbonate precipitation. These chemicals vary in type and include combinations of acids, chelators, and phosphate-based inhibitors. Each has advantages and disadvantages as described below.

Advantages:

- Phosphate-based chemicals are routinely and successfully used at drinking water treatment plant to inhibit scaling.
- Calcium carbonate precipitation is a function of acidity. Adding acids to water will reduce calcium carbonate precipitation.

Disadvantages:

- Non-phosphate based residential chemical conditioners lack quality, peer-reviewed evaluation of their performance.
- Common chemical chelators such as Ethylenediaminetetraacetic acid (EDTA) and citric acid add biochemical oxygen demand to the water. Adding biochemical oxygen demand to residential water encourages microbial growth and biofouling.
- Adding acids to water encourages corrosion of metal piping. The dosage of acid required would need to be carefully managed to prevent corrosion.
- It is unclear if the pH required to prevent calcium carbonate precipitation would be within acceptable drinking water pH values.

Cost

The average 10-year capital and operation and maintenance (O&M) cost per unit for each alternative is listed in Table 8 below, as taken from the report. TAC is cheaper than ion exchange. The costs of water conditioners were not evaluated because the technologies have not been shown to be valid.

Table 8. Costs of non-ion exchange softeners

Treatment alternative	Total annual O&M costs	Capital costs	10-year life-cycle cost
Electrically induced precipitation	$194	$2,375	$4,151
Magnetic water treatment	$11	$760	$855
Capacitive deionization	$102	$4,000	$4,873
Template assisted crystallization	$27	$1,098	$1,326
Ion exchange	$168	$2,048	$3,478
Water conditioners	NA	NA	NA

Increase residential softening target

Rationale

Ion exchange water softeners are designed to remove all hardness and to soften water to the minimum value of less than one grain per gallon of hardness.

Water that is moderately soft (3-5 gpg) can be aesthetically pleasing and meet residential needs. If the water supplied to a residence was only partially softened to 3-5 gpg, then the ion exchange column would receive less hardness loading and would need to be backwashed less frequently. This could provide a reduction in chloride loading to the WWTP.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

However, this option does not have the potential for a WWTP to meet its chloride limit. This is because most WWTPs in Minnesota that need to reduce their chloride discharges currently have concentrations well over the level needed to meet the standard. This method would reduce chloride buy 15-40% depending on source water, which is not enough to comply with the water quality standard in most cases.

This option is technically feasible. For example, Culligan produces a water softener with a bleed valve that allows for changing the target of water softening in homes.

WWTP chloride treatment

RO effluent - concentrate discharged to surface water

Rationale

RO is used to physically remove chloride from effluent. The concentrate from the RO system would be discharged to the receiving water for the WWTP discharge.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

This option has the potential for a WWTP to meet its chloride limit.

This option is technically feasible. RO at WWTPs has been successfully operated in California.

This option has some significant implementation concerns, especially with respect to how to manage and permit the RO concentrate:

- It is standard practice for the MPCA to require Whole Effluent Toxicity (WET) testing for RO concentrate discharged to surface waters. It is the experience of the MPCA that untreated RO concentrate is certain to fail acute and chronic WET testing discharge requirements. The MPCA cannot permit new NPDES discharges for which the permittee is certain to fail WET testing requirements. It would be the responsibility of the permittee to ensure that any discharge of RO concentrate would pass all WET testing.
- RO concentrate has high salt concentrations. It is the experience of the MPCA that RO concentrate frequently fails to meet Classification 3 and 4 water quality standards for salty parameters, especially TDS, bicarbonate and hardness. The surface water discharge would also need to comply with effluent limits based on the 230 mg/L Classification 2B chloride standard.

- The MPCA cannot permit new NPDES discharges for which the permittee is certain to fail water quality standards. It would be the responsibility of the permittee to ensure that any discharge of RO concentrate complied with Classification 2, 3 and 4 water quality standards.
- Complying with anti-degradation water quality standards would also be required for a new RO concentrate discharge to surface water to be authorized.
- A WWTP could choose to install a pipeline to transport RO concentrate to a receiving water with high assimilative capacity, such as a high flow river with low chloride concentrations. This option has been done in Minnesota to meet phosphorus limits, but is expensive and not a true way to eliminate the chloride problem. Permitting and financing this option is theoretically possible but would be difficult. Piping RO concentrate to a river body with high assimilative capacity for chloride should be considered a design option of last resort. It is not a good use of water resources.

Cost

The costs for this analysis were not calculated because this option was not considered feasible because of NPDES permitting regulations.

RO effluent - concentrate crystalized/evaporated

Rationale

RO is used to physically remove chloride from the effluent. The concentrate from the RO system would discharge to an evaporator/crystallizer. The evaporator/crystallizer would evaporate the water leaving a more solid, concentrated brine that could be disposed of in a landfill.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

This option has the potential for a WWTP to meet its chloride limit.

This option is technically feasible. However, it should be noted that land drying of RO concentrate is not feasible due to low yearly evaporation rates in Minnesota.

This option has some significant implementation concerns, especially with respect to energy use associated with evaporating/crystalizing the RO concentrate:

- The evaporated/crystalized brine needs to be disposed of in a landfill or be re-used somehow. Cities would need to develop plans with state and county solid waste authorities and the solid waste industry.
- It requires a tremendous amount of energy to evaporate/crystalize RO concentrate. A personal communication with a design engineer at Bolton and Menck found that a small WWTP (~1 million gallons per day) would require the energy from four large windmills continuously to operate.
- The city would need to develop the infrastructure to deliver large amounts of energy to the evaporator/crystallizer.
- Unless the source of energy for the evaporator/crystallizer is carbon neutral, the operation would increase greenhouse gas emissions.

Cost

In 2018, the MPCA commissioned an investigation that determined the costs and implementation concerns associated with using RO with evaporation and crystallization to treat salts at end of pipe. The results of that study can be found at https://www.pca.state.mn.us/sites/default/files/wq-rule4-15pp.pdf on the MPCA webpage and was funded by the Minnesota Environment and Natural Resources Trust Fund.

The study allowed the MPCA to make the following conclusions:

- The reverse osmosis process is complex and the equipment is difficult to maintain.
- The equipment for the evaporative process is extremely expensive to build and has a high energy demand.
- The salt waste that is left over at the end of the reverse osmosis process is very expensive to manage and dispose of.
- No MN city could afford to use RO with evaporation/crystallization at their wastewater plant.

The study estimated the following generalized cost for treating wastewater using RO with evaporation and crystallization. These costs are additional costs beyond secondary treatment and assume that the full wastewater stream is being treated. Contact the MPCA for specifics on how these figures were calculated.

Figure 11. Additional Capital Costs to treat with RO end of pipe.

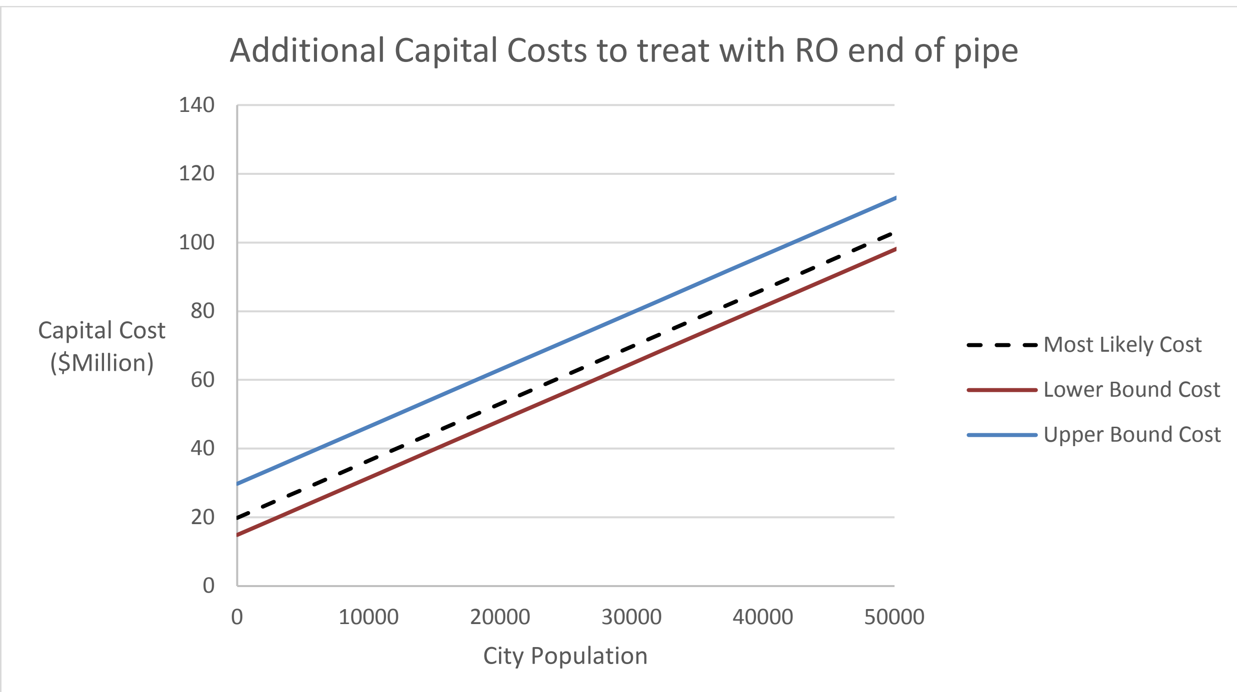
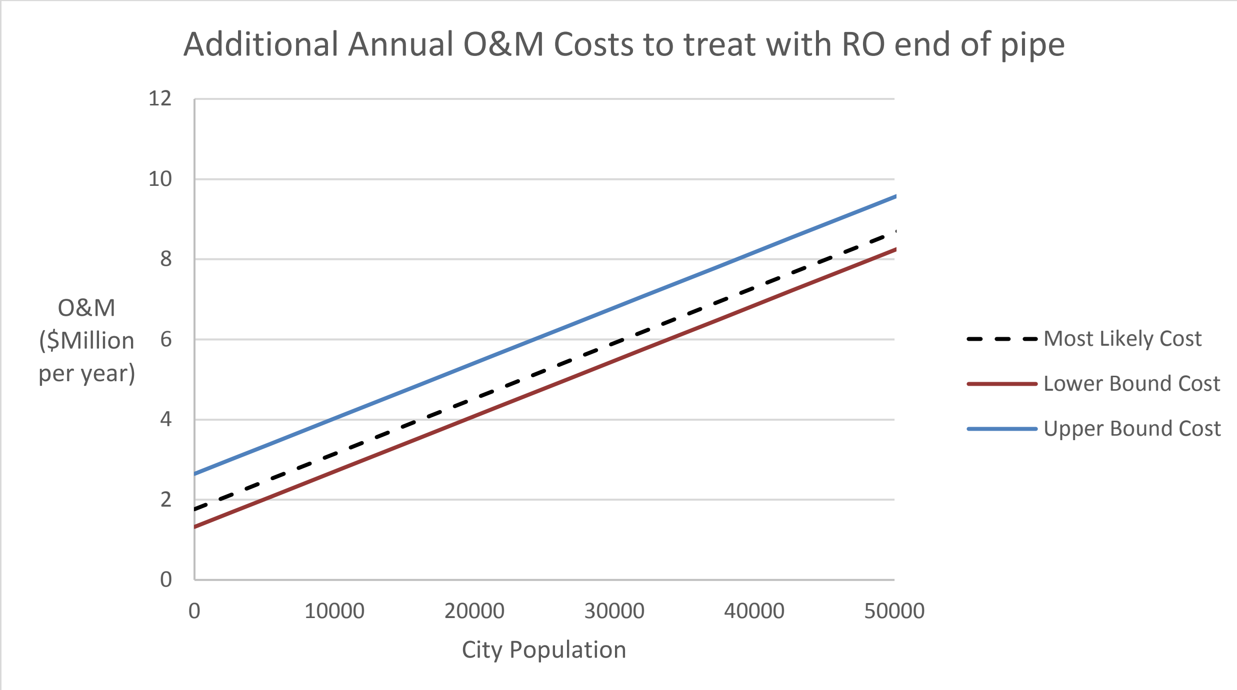


Figure 12. Additional Annual O&M Costs to treat with RO end of pipe.



RO effluent – concentrate deep well injection

Rationale

RO is used to physically remove chloride from the effluent. The concentrate from the RO system is injected into the ground for deep well disposal.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

This option has the potential for a WWTP to meet its chloride limit.

This option is technically feasible. Deep well injection of RO concentrate is practiced in California.

However, this option is not feasible in Minnesota because injection of waste into the ground is illegal.

Costs

The costs associated with this option were not calculated because it deep well injections are illegal in Minnesota.

Switching from chloride containing additives to additives without chloride

Rationale

WWTPs frequently use additives such as ferric chloride or aluminum chloride hydroxide as coagulants in their treatment systems. If a drinking water plant were to switch to an additive such as ferric sulfate or alum that does not contain chloride, then chloride loading to the WWTP would ultimately be reduced.

Feasibility

This option has the potential to reduce chloride loading to the WWTP.

However, this option does not have the potential for a WWTP to meet its chloride limit. A reduction in chloride concentrations in the WWTP effluent less than 25 mg/L is theoretically possible, assuming the WWTP plant uses additives that contain chloride.

This option is technically feasible.

Switching to coagulants that do not contain chlorides is feasible for many coagulants. The non-chloride containing versions of these additives are often similar in function.

Cost

Switching to chloride-free versions of certain chemicals is a cost-effective option because many of the non-chloride versions are cost competitive compared to the chloride-containing version and could be dosed using the same equipment.

Chlorination to UV disinfection

Rationale

Chlorine used to disinfect effluent ultimately decays to chloride, which increases chloride concentrations in the WWTP effluent.

If a WWTP switches from using chlorine to UV disinfection, then chloride loading would decrease in the WWTP.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

However, this does not have the potential for a WWTP to meet its chloride limit, unless the chloride concentration of the WWTP is very close to the limit that would comply with the 230 mg/L standard.

This option is technically feasible. There are many WWTP in Minnesota operating UV disinfection.

This option would be expected to reduce chloride concentrations somewhere between 10 and 20 mg/L, but depends on chlorine usage. The Santa Clarita, California, WWTP found that every 1 mg/L of chlorine removed reduces chloride concentrations by 1 mg/L.

Costs

Switching to UV disinfection is generally considered to be cost competitive with chlorine disinfection. UV disinfection has the advantage of eliminating the need to safely store and manage toxic chemicals on site at the WWTP.

Estimating the costs of switching to UV disinfection from chlorine is difficult because the costs are extremely dependent on the WWTP flow rate, site characteristics, and water quality among other factors. Nevertheless, there are many WWTPs in Minnesota that have switched from chlorine to UV disinfection and found it to be cost-effective.

Chloride precipitation with silver nitrate

Rationale

Chloride can be precipitated from aqueous solutions through the following reaction.

$$AgNO_{3^{aq}} + NaCl_{aq} \rightarrow AgCl_s + NaNO_{3^{aq}}$$

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

This does have the potential for a WWTP to meet its chloride limit. However, there are many technical feasibility concerns:

- The solid silver chloride precipitate would have to be disposed of at a hazardous waste landfill.
- It requires about 3 mg of silver to precipitate 1 mg of chloride.
- The infrastructure to supply, produce and deliver large quantities of silver nitrate to WWTPs would need to be developed.
- Aqueous free silver ion is a potent biocide and residual free silver toxicity poses a huge concern.

This option is not technically feasible because of the reasons listed above.

Costs

Reliable costs on industrial scale silver nitrate are not available. A preliminary cost estimate assuming the market rate of silver of $17/ troy ounce was assumed for lack of better information. At this price, it would cost about $625 of silver per 1,000 gallons to reduce chloride concentrations in effluent wastewater by 100 mg/L.

This option is extremely expensive.

Chloride anion exchange

Rationale

Chloride can be removed from water using chloride anion exchange resins.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

There is uncertainty whether this option could comply with the 230 mg/L chloride limit.

This option is not technically feasible.

Chloride anion exchange is not a widespread technology and no known large-scale chloride anion exchange plants are known to operate in the United States. This option would also require regenerating the chloride anion exchange resin. Regeneration would likely involve the use of large amounts of high strength acids and bases that would need to be managed to comply with NPDES permit limits and safety concerns.

Costs

The costs associated with this option were not calculated because the option is not technically feasible and there is no available way to estimate costs. It is reasonable to assume that costs would be extremely high.

Electrodialysis

Rationale

Electrodialysis is a treatment process that uses electrodes and semi-permeable membranes to produce low dissolved salt water.

Feasibility

This option has the potential to reduce chloride concentrations from the WWTP discharge.

There is uncertainty whether this option could comply with the 230 mg/L chloride limit. There are functional Electrodialysis plants around the world that treat brackish and salty water to drinking water standards. However, none of these plants treat water from a municipal WWTP. High-level engineering design and testing would be required to make this option work.

Electrodialysis is not a feasible option for treating chloride.

Costs

The costs associated with this option were not calculated because the option is not technically feasible without a tremendous amount of design work and there is no available way to estimate costs. It is reasonable to assume that costs would be extremely high.

Biological treatment

Rationale

Chloride is not an ion that can be removed using biological treatment.

Feasibility

Chloride is considered a conservative substance with respect to biological treatment. There are no biological based treatment systems that could be engineered to treat chloride. For example, chloride is used as conservative tracer in water balance studies at WWTPs because it is unreactive chemically or biologically.

Treating chloride using biological techniques is not a feasible option.

Costs

There are no costs for biologically treating chloride because it is not possible.

Ranking of feasible alternatives

The most feasible options for WWTPs to comply with the 230 mg/L chloride standard are ranked below. These options consider a balance of cost, engineering feasibility, and implementation concerns.

1. Upgrade residences and business to high efficiency point-of-entry softeners
2. Centralized lime softening and disconnecting point-of-entry softeners
3. Centralized RO softening and disconnecting point-of-entry softeners
4. RO at WWTP with evaporator/crystallizer

The most feasible treatment alternative is upgrading residences to high efficiency water softeners. However, there are numerous caveats to this option that would make it a poor compliance alternative for many Minnesota municipalities. **When selecting this alternative, the MPCA would likely require a professional engineer to formally sign plans that demonstrate that upgrading to high efficiency softeners is a feasible compliance alternative for the specific municipality in question.**

Considerations for upgrading to high efficiency softeners:

- WWTP effluent chloride concentrations should be within 100 mg/L of permit limits. In other words, the WWTP only needs a small reduction in chloride loading for full compliance.
- The majority of residences would be switching from inefficient softeners to high-efficiency softeners.
- Making progress toward permit limits is not enough. The engineering plan must ensure full and long-term (20-plus years) compliance with final chloride permit limits.

- A cohesive plan for upgrading residential water softeners would be necessary and must be signed by a professional engineer licensed in Minnesota.

The MPCA sees centralized lime softening and disconnecting point-of-entry softeners at the drinking water plant as the second most feasible option because:

- It allows for final compliance with permit limits if correctly implemented
- It's a common technology in Minnesota

This option should work providing that after a municipality starts centralized water softening:

- All residential water softeners are disconnected
- Inflow and infiltration are managed
- Industrial chloride loading is managed

The MPCA would probably not require a professional engineer to sign off on this plan.

Centralized RO softening and disconnecting point-of-entry softeners was ranked third because the RO concentrate stream would need to be managed and or treated, making the option less feasible than lime softening for most Minnesota municipalities.

Using RO at the effluent of the WWTP and installing evaporator/crystallizers was ranked fourth because this option is technically feasible but would incur significantly more costs on the community than the other higher ranked options.

This analysis does not consider using a combination of the listed alternatives to comply with the chloride limit. A combination of several of the listed alternatives could be effective in complying with the chloride water quality standard. However, a detailed site-specific analysis for each WWTP would be required. It is unlikely that a blanket combination of these alternatives would work for every WWTP.

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