Costs and benefits of household water softening: a review

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Introduction

Fresh waters across North America are becoming saltier and the salinity of surface waters and groundwater is an emerging environmental concern. Research has shown that salinization has affected over a third of the drainage area of the contiguous United States (Kaushal *et al.* 2018) and that thousands of water bodies in North America are at risk of long-term salinization (Dugan *et al.* 2017). Chloride contributes to salinity, and many streams in the United States have demonstrated long-term increases in chloride concentrations (Mullaney *et al.* 2009, Kaushal *et al.* 2005). In Minnesota, 50 surface water bodies exceed water quality standards for chloride, and long-term increases in groundwater chloride levels have been observed in many groundwater monitoring wells, some of which provide drinking water (MPCA 2018a).

Use of ion-exchange water softeners has been identified as a major source of chloride to Minnesota surface waters and groundwater (MPCA 2016). Households commonly use ion-exchange water softeners to remove ions that cause water hardness, primarily calcium and magnesium. Sodium chloride salt is typically used in the ion exchange process and is eventually discharged to either wastewater treatment plants (WWTPs) or septic systems. In Minnesota, residential water softener use is prevalent due to high hardness of groundwater resources (MPCA 2016).

Softened water provides numerous benefits to consumers but can have negative impacts on the environment. Chloride discharged from water softeners enters surface waters and groundwater and gradually accumulates over time, affecting the quality of water resources and health of aquatic environments. Little research has investigated the economic costs and benefits of water softening, and there is little information available on the environmental impacts of water softening. A review of literature was conducted to characterize the estimated costs and benefits of water softening to households and to society. All costs reported have been adjusted for inflation using the Consumer Price Index (Bureau of Labor Statistics 2018) and from other currencies to USD using conversion rates from OANDA Corporation (OANDA Corporation 2018).

Household costs of hardness and water softening

Hardness in drinking water has direct economic effects on households, as hard water requires more soap to produce lather and can cause staining in washed clothes. Classifications of water hardness are found in Table 1. In estimating damages for residential water use in the United States, Tihansky (1974) estimated that water hardness accrued $6.13 billion in damages nationwide each year, largely due to costs from extra soap and detergents. Additionally, hardness ions in water can build up in appliances and fixtures, reducing the lifespan of household appliances such as dishwashers, coffee makers, and washing machines (Godskesen *et al.* 2012, Van der Bruggen *et al.* 2009).

Table 1. Standard water hardness classification (ASABE 1999).

Degree of hardness	Hardness in grains per gallon (gpg)	Hardness in parts per million (ppm) or mg/L $CaCO_3$
Soft	<1.0	<17.1
Slightly hard	1.0 - 3.5	17.1 - 60.0
Moderately hard	3.51 - 7.0	60.1 - 120.0
Hard	7.01 - 10.5	120.1 - 180.0
Very hard	>10.5	>180.0

Several older studies have examined the economic impacts of water hardness on household expenditures. Annual per capita damages in areas of the United States with water hardness over 400 ppm were estimated at $148 ((Metcalf and Eddy 1972) as cited in (Tihansky 1974)). This estimate included costs of increased use of cleaning products and reduced water heater lifespan but did not include damages from water hardness on other household fixtures and appliances, so it likely underestimates household damages from hardness. Other studies examined the annual per capita cost of cleaning products caused by each 100-ppm increase in water hardness, and estimates range from $10 to $54 per 100-ppm increase with a mean estimate of $28 (Tihansky 1974).

Water hardness can also affect commercial and industrial organizations. Scale in boilers can reduce thermal efficiency (Lee *et al.* 2002, Paul *et al.* 2009) and lifespan (Widder and Baechler 2013) of boilers. Compared to water heaters using softened water, operation costs of gas and instantaneous water heaters using water with 513 ppm hardness have been found to cost $837 and $1,734 more, respectively, over their 30-year lifespans (Paul *et al.* 2009).

Damage caused by hardness in drinking water can be mitigated by water softening. Softened water produces many savings to households, including: savings on fuel for heating water; treating scale on plumbing; extended clothing life; and fewer leaves and grounds to make tea and coffee ((Aultman and Larson 1958) as cited in (Aton 1973)). Households can soften their water supply through many methods but use of an ion-exchange water softener is the most common household treatment method. Fox *et al.* (2011) estimated 10-year life-cycle costs for new, high-efficiency water softeners as $4,000 for water with 150 mg/L hardness. The city of Bloomington, Minnesota, which has hardness of 325 ppm in its raw water (City of Bloomington 2017), estimated that softening cost $4.70 per 1,000 gallons using ion-exchange softeners, including costs of installation, operation, and maintenance (MPCA 2018b). Assuming household use of 7,500 gallons per month, homeowners were estimated to spend $35.28 monthly on water softening (MPCA 2018b).

Research in the United Kingdom (UK) has examined household water softening behaviors and costs. Lanz and Provins (2016) found that 14% of their survey respondents took measures to correct water hardness, typically by softening water, and spent an average of $127 (GBP 94) per household per year, with median spending of $68 (GBP 50). The range of water hardness in the study region was not discussed. Households spent between $8-11 (GBP 6-8) annually per 100 ppm hardness in averting expenditures such as water softening (Lanz and Provins 2016). Lanz and Provins found that more households were motivated to treat water for aesthetic qualities, like taste and smell, but spent more money on water softening than on treatment for aesthetic qualities.

Water softening provides additional benefits beyond hardness removal. Water softeners remove iron and radionucleides from water, which in some areas are naturally occurring and present in groundwater. Iron can cause staining of sinks and fixtures, affect taste of drinking water, and contribute to pipe blockages, and long-term exposure to high radionucleide levels can have many negative health effects. Removal of iron and radionucleides contributes to the economic benefits of water softening, which have not been estimated in recent research.

Economic impacts of water softening on water resources

While direct benefits of water softening to households may offset the damages of water hardness, there are wider impacts of water softening with costs to society. Accumulation of chloride in groundwater and surface water over time can lead to degradation of water quality and aquatic ecosystems, which have wider economic costs to society. Economic benefits derived from water use may include: water withdrawal for consumption or use; in-stream benefits, such as recreation; aesthetic benefits; or ecosystem services such as habitat provision.

The economic benefits of water quality are often estimated individually and are rarely assessed together in research (Keeler *et al.* 2012), so there is limited research to estimate the economic costs of water softening based on its water quality effects. However, relevant findings from literature on chloride and other water quality concerns are illustrative of economic valuation of water quality.

Groundwater

Contamination of private and public water supplies

Water softeners that discharge to septic systems can introduce chloride to groundwater resources, which are often drinking water sources. In Minnesota, groundwater serves as the drinking water source for 75% of residents (MDH 2017). Kelting and Laxson (2010) estimated the ecosystem service value of groundwater in northern New York by placing a value on $0.12 per gallon of groundwater, with $0.06 for base water and $0.06 for water treatment through natural filtration. Applying this value to the estimated 266-349 million gallons of groundwater pumped per day in the Twin Cities Metropolitan Area (Freshwater Society 2017), the ecosystem service value of groundwater in the metropolitan area can be estimated at $11.7-$15.3 billion per year.

Water with elevated chloride has a salty taste and the Environmental Protection Agency (EPA) set a secondary drinking water standard for chloride at 250 mg/L. Costs incurred from increasing salinity of groundwater are available from studies examining economic impacts of deicing salt infiltration. Although the costs from deicing salt infiltration and softener discharge to septic systems are not directly comparable due to different application rates and areas, they are illustrative of mitigation costs for elevated chloride levels in groundwater.

In cases where salinity of drinking water sources makes them unsuitable for drinking water, costs may be incurred by drilling wells to different aquifers, piping in water from nearby sources, or in some cases, distillation of water (Buckland and McGhie 2005). Between 1983 and 1990, the Massachusetts Department of Public Works (MDPW) received complaints from approximately 100 of the 351 municipalities in Massachusetts of salt contamination of public and private water supplies (Pollock 1992). The MDPW spent approximately $2.2 million to remediate private water supplies that were found to be contaminated by winter maintenance operations (Pollock 1992). Additional mitigation measures included connecting households to public water supplies and installing temporary reverse osmosis filters (Transportation Research Board 1991). A survey of state highway departments in 1989 found that across nine northern states with high deicing salt use, nearly $3.4 million were spent annually on mitigating contamination of drinking water by road salt, or an average of $1.86 per ton of salt applied (Transportation Research Board 1991). These measures included actions such as upgrading deicing salt storage and replacing private wells (Transportation Research Board 1991). Between 1998 and 2003, the New Hampshire Department of Transportation replaced over 424 private wells contaminated by road salt from 1998 to 2003, costing $3.2 million, and several public water supply wells were discontinued due to contamination (NHDES 2017).

Anderson and Auster (1974) estimated the costs of salt contamination on a national scale. Given that at the time, national water consumption was approximately 25 trillion gallons per year, they estimated that contaminating 10% of the national water supply would result in price increases of 25% and loss of $1 billion (Anderson and Auster 1974). The authors expected this estimate to be high due to potential of reusing wastewater or augmenting supply from distant sources and acknowledged there was little evidence of higher water prices due to salt contamination. However, the estimates by Anderson and Auster illuminate the magnitude of theoretical national costs from widespread salt contamination.

Saline water supply can cause damage to municipalities, industries, and commercial organizations, and these costs were estimated for the Murray-Darling Basin in Australia using total dissolved solid (TDS) levels. The highest household costs were incurred by damage to hot water systems, at 27 cents per mg/L TDS per year, followed by rainwater tanks at 14 cents per mg/L TDS per year. Other household costs included (in decreasing order): damage to water pipes and fittings; corrosion of water taps; damage to shower fixtures; water softeners; and water filters. Industrial and commercial water users accrued the highest costs from damage to boiler feed and cooling towers ((Wilson and Laurie 2002) as cited in (DIPNR 2005)).

Increased salinity of groundwater can also affect agriculture and lead to higher costs for irrigation. Elevated salinity of irrigation water can incur damages from declining yields or implementing management options to mitigate soil-water salinity content (Kleinman and Brown 1980). Mukherjee and Schwabe (2014) found that farmland market values in Central Valley, California declined with increasing salinity levels.

The replacement cost of drinking water with elevated chloride can be estimated using desalination costs. A report from the California Public Utilities Commission estimated desalination costs at \$3,600 per acre-foot of drinking water, approximately four times the cost of traditional water sources (CPUC 2016).

Health implications

Sodium chloride salts are commonly used for water softening. Sodium intake can contribute to hypertension, a major risk factor for cardiovascular disease. The EPA requires monitoring of sodium levels in public water supplies and reporting when sodium levels exceed 20 mg/L for notification of patients on sodium-restricted diets (U.S. EPA 1996). The amount of sodium in tap water is typically low, but ion exchange softening can add sodium to drinking water. The amount of sodium in drinking water from water softening is minimal compared to an average diet and has little effect on healthy individuals but may be a concern to individuals with hypertension on low sodium diets. Analysis of health costs from sodium in drinking water was conducted by the state of Massachusetts by estimating bottled water costs for the at-risk population and estimate of excess deaths. These were estimated at \$55 per ton of salt ((Massachusetts Department of Public Works 1989) as cited in (Vitaliano 1992)).

Elevated chloride in drinking water can lower pH of water and accelerate deterioration of pipes, which can increase the rate of lead release from water distribution pipes (Stets *et al.* 2017). Lead in drinking water has public health implications due to its myriad health effects, including effects on learning and behavior in children and on cardiovascular, kidney, and reproductive health in adults (U.S. EPA 2017). Corrosion caused by elevated chloride levels in drinking water supplies could incur costs from replacement of pipes and fixtures and health effects from elevated lead in drinking water.

Surface waters

Surface waters provide many ecosystem services, such as recreation and water supply for municipal, agricultural, and industrial users. Costanza *et al.* (1997) estimated ecosystem services from lakes and rivers from available literature and sources, shown below in Table 2.

Table 2. Average value of lake and river ecosystem services. Adapted from (Costanza *et al.* 1997)

Ecosystem service	**Ecosystem service examples**	**2018 USD $ha^{-1}yr^{-1}$**
Water regulation	Provision of water for agricultural or industrial processes	9,331
Water supply	Provision of water by watersheds, reservoirs, and aquifers	3,628
Waste treatment	Nutrient recovery, removal, or breakdown	1,140
Food production	Supporting growth of food products	70
Recreation	Eco-tourism, sport fishing, and outdoor recreational activities	394
Total value		14,563

No studies have examined economic damages from elevated chloride levels in surface waters, but literature values on willingness to pay for surface water ecosystem services provide useful reference. A study of the South Platte River in Colorado examined its ecosystem services of wastewater dilution, natural water purification, erosion control, fish and wildlife habitat, and recreation, and found that mean willingness to pay (WTP) for restoring ecosystem services along a 45-mile stretch of river was estimated at $24 per month, or $288 annually (Loomis *et al.* 2000). Loomis *et al.* (1987) reported similar WTP values in other studies of ecosystem services, ranging from $227 annually for the Monogehela River (Desvousges *et al.* 1983) to $608 for Mono Lake. Although WTP may not be generalizable to other surface waters due to differences in ecosystem services provided and community characteristics, the estimates are illustrative of consumer valuation of water body ecosystem services.

Aquatic ecosystems

Research has shown that high chloride levels affect many species, although the economic damages from elevated chloride levels in aquatic ecosystems have not been examined in research. Lower amphibian survival rates (Dougherty and Smith 2006, Karraker *et al.* 2008), aquatic insect diversity (Demers 1992), algal density (Dickman and Gochnauer 1978), and bacterial density (Dickman and Gochnauer 1978) have been found in ecosystems with high chloride concentrations. Relationships have also been established between elevated chloride concentrations and lower species richness among macroinvertebrates (Williams *et al.* 1997) and bog and marsh vegetation (Miklovic and Galatowitsch 2005, Richburg *et al.* 2001, Wilcox 1986). Research has shown that flathead minnows have been affected by chronic chloride concentrations of 298 mg/L (Birge *et al.* 1985). Sensitive species such as daphnia taxa are impacted by chloride concentrations as low as 194 mg/L, and chloride levels of 327 mg/L and 451 mg/L have impacted snails (*Physa gyrina*) and caddis flies (*Anabolia nervosa* and *Limnephilus stigma*) (Evans and Frick 2001). At high concentrations, chloride can be toxic to spotted salamanders (Collins and Russell 2009), wood frogs (Collins and Russell 2009), bluegill sunfish (Evans and Frick 2001) and rainbow trout ((Spehar 1987) as cited in (Benoit 1988)).

The EPA set water quality standards for chloride at 230 mg/L to protect aquatic life. Since chloride has been found to affect many species and their health and survival may have wider ecosystem effects, it could be expected that chloride-impaired waters may incur substantial damages from ecosystem effects. However, assessing economic damage from chloride levels in surface waters is complicated by several factors. Streams may experience increases in chloride throughout the year that are nontoxic to aquatic life, and while they may affect the species present in the stream, they may not result in widespread ecological damage (Transportation Research Board 1991). These subtle changes can be difficult to observe and complicate estimation of their economic effects (Transportation Research Board 1991).

Recreation

Chloride-impaired rivers and lakes could experience economic losses from decreased recreation. Aquatic ecosystems with high chloride may not support fishing and may have aesthetic damage that could impact camping revenue. Vitaliano (1992) estimated that road salt application caused $136 per ton in aesthetic damages due to tree damage in the Adirondacks region and lost revenue from camping.

While there is little other research examining economic impacts of elevated chloride on recreation, particularly from water softener discharge, recreation can be an important revenue source. For example, annual recreational benefits from improved water quality relating to lake nutrient levels in St. Albans Bay were estimated at $302 for visitors, a recreation site for fishing, boating, and swimming (Ribaudo and Epp 1984). In Minnesota, the fishing industry supports 43,000 jobs and generates $3.2 billion annually in direct expenditures, or above $5.3 billion when including indirect expenditures such as gas and lodging (MNDNR 2011). Elevated chloride in lakes, rivers, and streams could have consequences for fishing and tourism at state and local levels.

Property values

Impairments for surface waters can also affect property values. No studies have examined effects of chloride impairments on property values, but estimates from published research on other water quality impairments provide useful comparison. Studies have shown that property values have been impacted by water quality measures such as clarity (David 1968, Steinnes 1992, Feenberg and Mills 1980) and fecal coliform bacteria levels (Leggett and Bockstael 2000), and research has shown that water quality measures such as these can be used to assign economic value to water quality (Egan *et al.* 2009). However, chloride does not impact water clarity or have a direct public health impact. Effects of pH levels may be more comparable to chloride, since they do not have direct impacts on water clarity or have public health implications. Epp and Al-Ani (1979) examined stream acidity in rural Pennsylvania and found that pH levels had significant effects on property values in clean streams due to their effects on recreational activities, such as trout fishing.

Costs of chloride reduction strategies

Water softening can have many downstream effects that have direct and indirect costs to communities. Chloride introduced from water softening can be reduced through decreased salt use or through municipal water or wastewater treatment.

Reduce water softening salt use

Replacement or optimization of household water softeners can decrease the amount of salt needed to soften water. Older water softeners that regenerate based on timers are less efficient and use approximately 50% more salt than newer models that regenerate based on water use. A study in Madison, Wisconsin examined chloride loading from water softeners and observed chloride loading reductions of 27% and 47% in sewersheds where water softeners were optimized and replaced with high-efficiency units, respectively (Lake *et al.* 2015).

The study also compared the household costs of optimization and replacement. Optimization measures cost between $95-235 per household (average $190) and included: refilling salt, cleaning and refilling brine tanks, reconnecting or cleaning blocked hoses, adjusting salt dosage or regeneration time, replacing brine tanks, recalibrating hardness, setting up or repairing floats, and replacing gaskets (Lake *et al.* 2015). The home visit cost from water softening professionals was the largest optimization cost; costs of refill salt, parts, and repairs were relatively small in comparison. In comparison, softener replacement cost an average of $1,422 per household. Taking into account chloride reductions, optimization was found to be the most cost-effective measure for chloride reduction, costing $2,752 per 1 kg chloride reduction compared to $12,118 per 1 kg chloride reduced through water softener replacement (Lake *et al.* 2015).

There are technologies available commercially that do not use salt and may reduce formation of scale in appliances and fixtures. These units are often less expensive than ion-exchange water softeners (Table 3), although the efficacy of non-salt water treatment methods in reducing scale build-up is not well established. Fox *et al.* (2011) found that among non-salt water conditioners, template-assisted crystallization achieved 88% reduction in scale formation compared to no water treatment, and electrically induced precipitation and magnetic water treatment reduced scale formation by 50%.

Table 3. Average capital, operation and maintenance, and life-cycle costs of water conditioners. Adapted from (Fox *et al.* 2011); all costs in 2018 USD.

Treatment type	Capital costs	Average annual operation and maintenance costs	Average 10-year life-cycle cost
Water softening			
Ion exchange	2,246	186	3,844
Non-salt water conditioning			
Electrically induced precipitation	2,625	214	4,588
Magnetic water treatment	840	12	945
Capacitive deionization	4,421	113	5,386
Template assisted crystallization	1,214	30	1,466

Since salt is inexpensive, the savings from reduced softening salt use in households are relatively minor. However, industries and commercial organizations that have high water use may have substantial savings from measures to reduce softening salt. Several commercial case studies from Madison illustrate these savings. Installation of a hardness monitor at a laboratory the University of Wisconsin-Madison resulted in a 35% reduction in salt use, and the hardness monitor had a 7.5-month return on investment (MMSD 2017). Brine reclamation used by Pfizer in Madison reduced salt use by approximately 20%, saving nearly 20,000 lb of salt annually and resulting in a cost recovery for the brine reclamation unit in about 2.5 years (MMSD 2017). Additionally, savings from reduced salt use are greater in areas with high water hardness than in areas with softer water.

Centralized softening of drinking water

Lime softening

In some municipalities, drinking water is softened before distribution to households. Lime softening of drinking water is a common form of centralized water softening and has many advantages, including disinfection, removal of iron and manganese along with hardness, and reduction in dissolved solids (Aton 1973). In lime softening, lime is added to the water, increasing pH and causing precipitation of hardness-causing ions.

Minnesota Pollution Control Agency (MPCA) conducted a cost analysis of multiple options for reducing chloride in surface waters (MPCA 2018b). Lime softening costs were estimated by the contracting firm Bolton and Menk, and general capital costs are shown in Figure 1; costs will vary across communities based on factors such as water quality. Costs to operate centralized lime treatment facilities were estimated and based on 10-hour working days for operators, sludge thickening of lime solids, a 20-year payment schedule for capital costs, an interest rate of 4%, and operations and maintenance (O&M) costs of $7 per 1,000 gallons of treated water (MPCA 2018b).

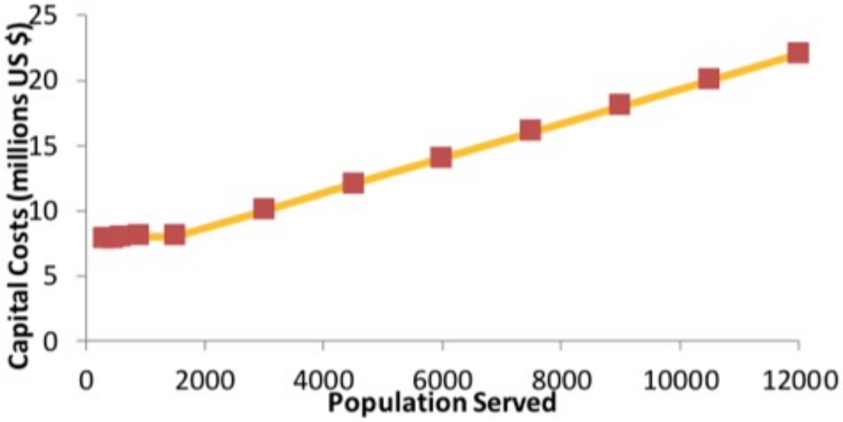

Figure 1. Capital cost of lime softening drinking water plant, by population. Adapted from (MPCA 2018b).

The costs of centralized water softening are often lower for households than ion-exchange water softening (Aton 1973, Howson 1962). Using ion-exchange water softeners cost homeowners in Bloomington, MN approximately $1.21 more per 1,000 gallons than centralized water softening (MPCA 2018b), and assuming household water use of 7,500 gallons per month, households could save approximately $9 per month using centralized water softening. However, the City of Bloomington softens water to 89 ppm hardness (City of Bloomington 2017) and households may continue to soften their water to remove additional hardness.

Centralized water softening is not a solution for all communities. The annualized costs of centralized water softening, including capital, operation, and maintenance, are higher for smaller communities, as seen in Figure 2. The costs and benefits from centralized water softening depend on many factors, including water quality and how many households soften water. Using data from a survey of utility managers from several cities in Wisconsin, Howson

(1962) estimated prevalence of water softener use based on water hardness, although the vertical location of the line on the graph was expected to differ by communities based on factors such as community economic status and cost and availability of water softeners (Figure 3). Metcalf and Eddy (1972) also examined this relationship by surveying households from ten communities in California, Texas, Florida, and Colorado (Figure 3; $R^2 = 0.880$). The difference in softening estimates may be attributed to regional differences in water softening practices or to the data collection methods used in the studies.

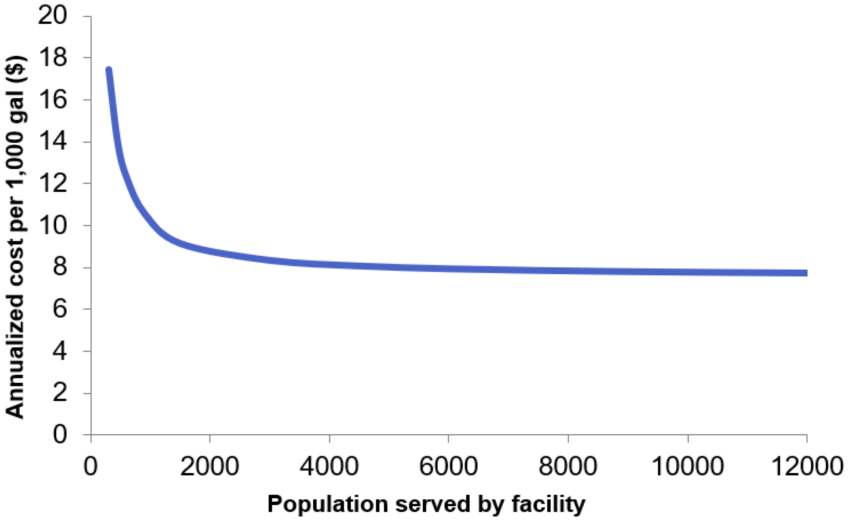

Figure 2. Annualized cost per 1,000 gallons of lime softening drinking water plant capital and operation and maintenance, by population. Adapted from (MPCA 2018b).

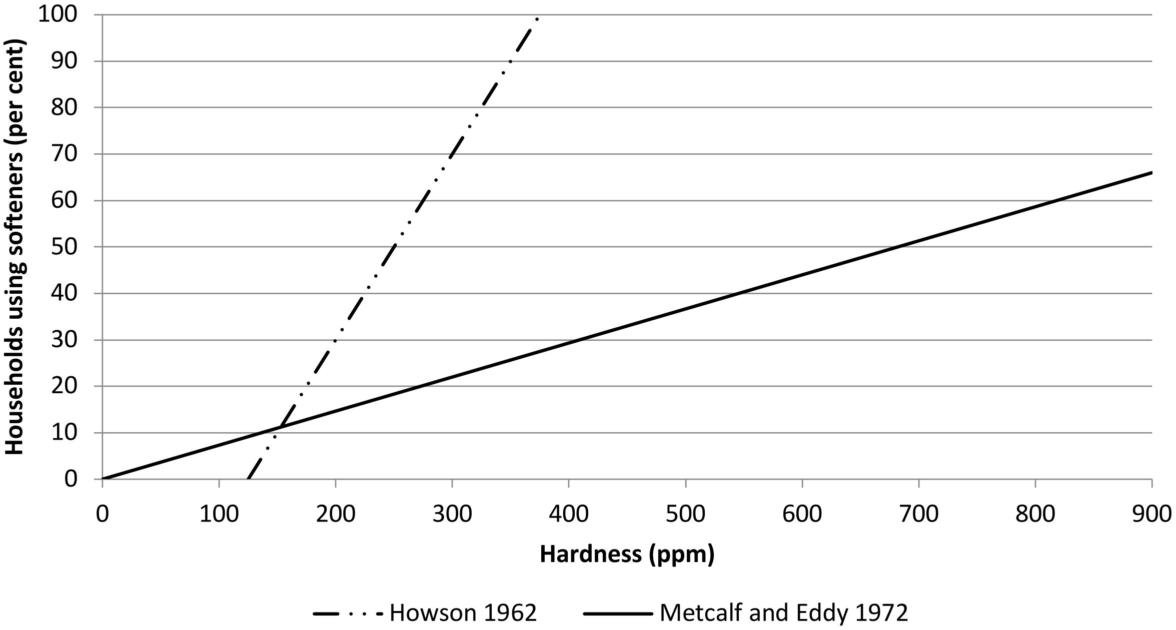

Figure 3. Literature estimates on prevalence of water softener use based on water hardness. Adapted from (Howson 1962, Metcalf and Eddy 1972).

Several studies analyzing costs and benefits of centralized softening have been conducted in Europe. In addition to capital and operation and maintenance costs of centralized softening, a cost-benefit analysis in Flanders, Belgium examined the following costs: reduced use of detergents for household appliances; reduced appliance cleaning from hardness fouling; increased lifespan of appliances; energy consumption; environmental effects from softer water, reduced salt levels, lower water use, and reduced energy consumption; and employment effects (Van der Bruggen *et al.* 2009). While substantial savings were gained from reduced cleaning of fouled appliances and reduced detergent use, the greatest household savings were achieved through not using domestic water softeners (Table 4). Taking into account the cost of water, net annual savings for average families were estimated to be $143 (Van der Bruggen *et al.* 2009).

The level of water hardness after treatment was found to be the most important factor for establishing costs, and the break-even point was found to be a hardness reduction (or, softening depth) of 50 ppm (Van der Bruggen *et al.* 2009). Hardness in the region was 470 ppm, and central softening to 150 ppm was under consideration. Other studies have found low break-even points for centralized softening; results from a life cycle assessment of centralized water softening costs in Copenhagen indicated a minimum hardness reduction of 22 ppm (from 362 ppm to 340 ppm) for an environmental break-even point (Godskesen *et al.* 2012). This small softening depth indicated that environmental benefits were achieved rapidly, and greater softening depths were recommended for additional household benefits (Godskesen *et al.* 2012). Although these studies demonstrate the benefits of centralized water softening including wider household and environmental benefits, their savings estimates may not be wholly generalizable to the United States due to differences in water treatment technologies and their costs and availability.

Table 4. Benefits of centralized softening for drinking water customers in Flanders, Belgium. Adapted from (Van der Bruggen *et al.* 2009).

Household savings from centralized softening	**Annual household savings (2018 USD)**
Household products, total	37.32
Salt avoided for dishwasher softener	9.03
Soap avoided for washing clothes	16.70
Powder avoided for clothes washer	7.33
Softener avoided for clothes washer	1.70
Vinegar avoided for cleaning coffee machine	0.51
Vinegar avoided for cleaning kettle	1.02
Cleaning product avoided for cleaning bathrooms	1.02
Lifecycle and maintenance, total	20.11
Water heater	13.63
Clothes and dishwasher	2.22
Kettle and coffee machine	2.22
Bathrooms, sinks	2.05
Domestic softeners, total	86.58
Investment cost avoided	28.46
Salt cost avoided	23.35
Maintenance cost avoided	18.24
Water cost avoided	13.98
Electricity cost avoided	2.56
Energy consumption, total	15.51
Water heater savings	12.10
Clothes washer savings	2.39
Kettle savings	0.68
Coffee machine savings	0.34
Comfort, total	14.49
Bottle water for kettle	0.34
Bottle water for coffee machine	1.02
Time saved to clean the coffee machine	6.14
Time saved to clean the kettle	6.82

For cities that source groundwater from multiple wells, softening water at wellheads is an alternative to centralized water softening. In its analysis of chloride compliance alternatives for the city of Madison, WI, AECOM (2015) found that hardness removal at individual wellheads had the highest overall score among the treatment alternatives when weighed by financial, operational, environmental, and social/community aspects. The total life-cycle costs for wellhead treatment were estimated at $287.8 million, compared to $386.0 million for centralized water softening (AECOM 2015).

Reverse osmosis

Reverse osmosis (RO) is another treatment that can be used to centrally soften drinking water before distribution to households. RO employs membranes to filter drinking water and removes hardness as well as other contaminants.

Bolton and Menk estimated capital costs for new RO drinking water plants (Figure 5) as well as annualized costs including operation and maintenance, which incorporated a 20-year payback schedule for capital costs, a 4% interest rate, and cost of $4/1,000 gallons of produced water (MPCA 2018b). Costs of softening by RO are dependent on water quality, but this treatment may be an affordable option for small communities (Figure 6). However, RO has a high ratio of discharge water to produced water, and disposal of RO concentrate makes this treatment type less feasible to many communities compared to lime softening (MPCA 2018b).

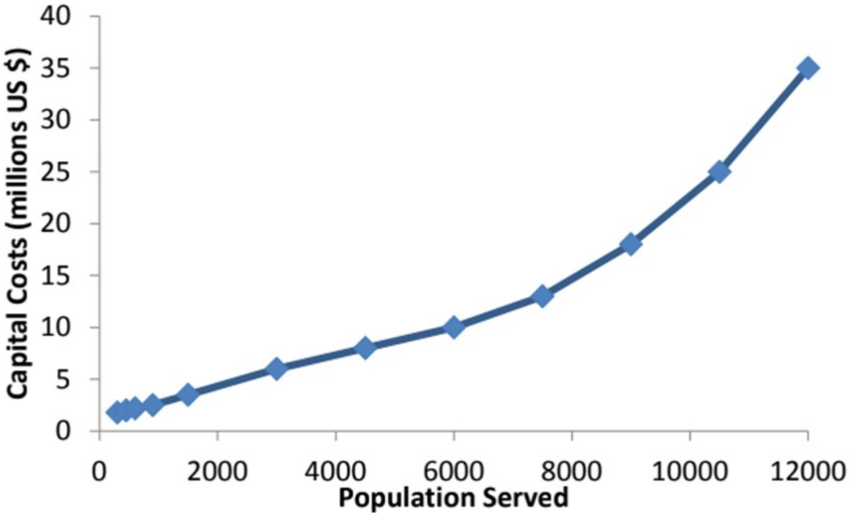

Figure 5. Capital cost of reverse osmosis drinking water plant by population. Adapted from (MPCA 2018b).

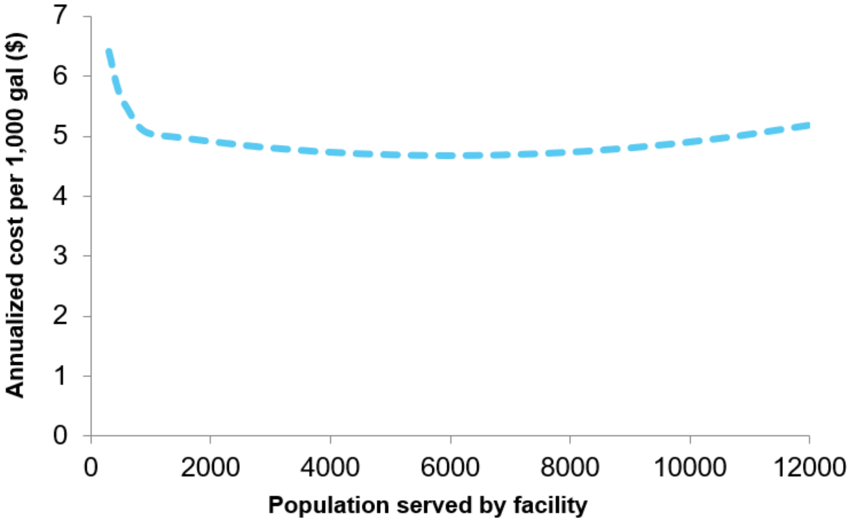

Figure 6. Annualized cost of reverse osmosis drinking water plant by population per 1,000 gallons. Adapted from (MPCA 2018b).

Additional wastewater treatment

In its analysis of chloride reduction alternatives, MPCA examined feasibility and cost of treating WWTP effluent to remove chloride, including RO treatment of wastewater effluent (MPCA 2018b). RO treatment was found to be generally infeasible due to its expense and regulations surrounding discharge of RO concentrate. Discharging concentrate to surface waters and injecting concentrate into deep wells are not feasible due to permitting regulations and legality, respectively. Crystallization and evaporation of concentrate was found to be feasible, but pre-treatment made the option very expensive, and centralized treatment of drinking water may be more affordable for some communities. Costs for RO with crystallization and evaporation were estimated using estimates from a permit application and assumed a 20-year payback and 4% interest rates (Table 5); costs were expected to be higher for smaller communities and lower for large communities (MPCA 2018b). In Madison, WI, RO treatment of wastewater was estimated to have life-cycle costs of $2,348.8 million, or $464.4 million for RO with brine minimization with evaporation and crystallization (AECOM 2015).

Table 5. Capital, operation and maintenance costs for reverse osmosis treatment of wastewater effluent. Adapted from (MPCA 2018b); all costs in 2018 USD.

Treatment type	Capital cost ($million per MGD)	Operation and maintenance ($)
Fine filtration pre-treatment	1.5	100-150 per million gallons
RO with evaporation and crystallization	26	2.35 per MGD per year

In Scottsdale, Arizona, the Advanced Water Treatment (AWT) facility uses reverse osmosis to decrease salinity in wastewater for golf course irrigation and groundwater recharge. Water softeners are major contributors to salinity in Scottsdale and reducing salinity from water softening by half would reduce operating costs of the AWT by up to $210,000 annually. The salt brine removed by the AWT is currently discharged to another wastewater treatment plant, and Scottsdale would need to invest $95 million in capital to further treat the brine and halt discharging salts to the environment (Scottsdale City Council 2014).

Additional chloride reduction measures at wastewater treatment facilities that were found to be potentially cost effective by MPCA included: switching from chloride-containing coagulants to coagulants without chloride and switching from chlorination of effluent to UV disinfection, although these were not expected to lead to dramatic chloride reductions. Precipitation of chloride using silver nitrate was found to be too expensive, and removal of chloride through anion exchange, electrodialysis, and biological treatment were found to be infeasible (MPCA 2018b).

Wastewater treatment facilities that are noncompliant with chloride water quality standards may incur steep costs. In Minnesota, approximately 100 WWTPs have reasonable potential to exceed the water quality standard of 230 mg/L (MPCA 2017). Facilities exceeding water quality standards may receive permits with limits on chloride discharge, necessitating action to obtain compliance with the standard. In analyses of compliance strategies and costs, the MPCA found that most communities with reasonable potential are smaller communities that are unable to afford capital-intensive projects to reduce chloride levels, such as reverse osmosis and evaporation and crystallization. Communities can apply for variances to provide extended time to comply with limits as long as water quality is not degraded. While variances can delay the expenses of compliance costs, they do have a one-time application fee of $10,800 (MPCA 2017). Noncompliance with WWTP limits is typically resolved through a Letter of Warning or Notice of Violation, but repeated violations of limits may lead to enforcement actions with monetary penalties (MPCA 2018c), and additional costs may be accrued through the time city personnel have to spend in resolving the issue.

Summary and discussion

Findings from research literature show that in addition to the aesthetic benefits of soft water, water softening provides economic benefits to households, commercial organizations, and municipalities through decreased damages to appliances and utilities from water hardness. However, no cost-benefit analyses of household water softening have been conducted that include its environmental impacts.

Relevant findings from literature indicate that the effects chloride from water softener discharge on water resources has direct and indirect economic costs. Research on deicing salt shows that costs to mitigate chloride contamination of drinking water supplies are high. The damages from chloride intrusion from water softening are likely substantially lower than deicing salt, since only a fraction of water softeners discharge to septic systems and contribute chloride to groundwater, but mitigation costs provide a useful metric for estimating damages from water softener discharge to septic systems. Little research has investigated the damages from elevated chloride concentrations in surface waters based on its effects on plant and aquatic life, but relevant findings from research on water quality valuation indicates that impaired waters can affect property values and recreational revenue, and that communities are willing to pay for ecosystem services from freshwater bodies.

Limited research has examined opportunity for chloride reductions through improving water softening efficiency. Replacement and optimization of water softeners led to substantial reductions in chloride loading in Madison, WI, and optimization was found to be the more cost-effective option. Chloride reductions from softener replacement and optimization in other communities will be dependent on factors such as water hardness and prevalence, age, type, settings, and maintenance of existing softeners. Softener optimization and replacement can also have economic benefits for commercial and industrial users with high water needs through reduced salt use and high cost recovery. No-salt water conditioners are available commercially and have comparable costs to ion-exchange softeners, but their efficacy at reducing effects of hardness is not widely established.

Chloride reductions can also be achieved through treatment of drinking water and wastewater at the municipal scale. Centralized water softening can be less expensive for households than ion-exchange softening but is often less affordable for smaller communities due to the high costs of capital, operation, and maintenance. Additionally, households may still use water softeners where centralized treatment does not remove all hardness, decreasing the chloride reductions. Additional treatment at wastewater treatment plants can remove chloride from wastewater effluent and reduce chloride loading to receiving waters; treating effluent with RO and using evaporators and crystallizers for salt disposal was found to be feasible but was estimated to have higher costs than centralized water treatment. Chloride reductions of each water treatment option differ, and their ability to attain water quality standards will vary by community.

Reducing salt use is the most cost-effective way to achieve reductions in chloride concentrations. Communities with elevated chloride in groundwater, surface water, or wastewater treatment plant effluent will have to tailor their chloride reduction strategies to attain water quality standards and achieve meaningful chloride reductions, and multiple reduction strategies may need to be employed. However, since chloride accumulates in water resources over time, each unit reduction in chloride has benefits to the environment and society at large.

Conclusions

- Softening water can provide economic benefits to households, industries, and municipalities, but there is limited evidence to characterize the environmental costs of brine discharge.
- Although little research has investigated economic impacts from elevated chloride concentrations in surface waters, many species are sensitive to chloride, and impaired waters may incur costs from ecosystem damage and its impacts on recreation and property values. Limited research on deicing salt also indicates that mitigation costs from chloride intrusion into private and public wells are high. Future research estimating damages from elevated chloride in surface waters and groundwater would address an important research gap.
- Optimizing water softener settings and replacing old water softeners can provide meaningful reductions in chloride loading, but reductions at the community scale are dependent on factors such as water hardness and age, type, settings, maintenance, and prevalence of water softeners.
- Centralized softening may have lower costs for households than use of individual water softeners in larger communities, but it is not affordable for all communities. Additionally, centralized water softening may not remove all water hardness, and households still using water softeners may lower potential chloride reductions.
- Costs and benefits of chloride reduction strategies will vary across communities based on characteristics such as water quality, population, and economic status. Communities with elevated chloride in groundwater, surface water, or wastewater treatment plant effluent may need to employ multiple strategies to achieve meaningful and cost-effective chloride reductions.

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