Optimizing the implementation of drinking water softening

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Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

DTU Environment

Optimizing the implementation of drinking water softening

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PhD Thesis

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PhD Thesis
June 2021

DTU Environment
Department of Environmental Engineering
Technical University of Denmark

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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk.

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Preface

The work presented in this PhD thesis was conducted at the Department of Environmental Engineering at the Technical University of Denmark (DTU Environment) from December 2016 to April 2021. The thesis was supervised by Professor Hans-Jørgen Albrechtsen and Associate Professor Martin Rygaard from DTU Environment, Market Director John B. Kristensen and Innovation Director Erik C. Wormslev from NIRAS A/S, and Planner Per Sand Rosshaug from HOFOR A/S.

The thesis is organized in two parts: the first part puts into context the findings of the PhD in an introductive review; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-IV**.

- **I** **Tang, C.**, Rygaard, M., Rosshaug, P.S., Kristensen, J.B., Albrechtsen, H.-J. Evaluation and comparison of centralized drinking water softening technologies: Effects on water quality indicators. *Submitted.*

- **II** **Tang, C.**, Merks, C.W.A.M., Albrechtsen, H.-J. (2019). Water softeners add comfort and consume water – comparison of selected centralised and decentralised softening technologies. *Water Supply* 19(7), 2088-2097.

- **III** **Tang, C.**, Godskesen, B., Aktor, H., van Rijn, M., Kristensen, J.B., Rosshaug, P.S., Albrechtsen, H.-J., Rygaard, M. (2021). Procedure for calculating the Calcium Carbonate Precipitation Potential (CCPP) in drinking water supply: importance of temperature, ionic species and open/closed system. *Water* 13(42).

- **IV** **Tang, C.**, Hedegaard, M.J., Lopato, L., Albrechtsen, H.-J. (2019). Softening of drinking water by the pellet reactor – Effects of influent water composition on calcium carbonate pellets. *Science of the Total Environment* 652, 538-548.

In this online version of the thesis, paper **I-IV** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

In addition, the following publications and conference contributions, not included in this thesis, were also concluded during this PhD study:

Tang, C., Rygaard, M., Albrechtsen, H.-J., submitted, Skal blødgøring af drikkevand ske på vandværkerne eller hos forbrugerne? DANSKVAND

Tang, C., Merks, C.W.A.M., Rosshaug, P.S., Kristensen, J.B., Rygaard, M., Albrechtsen, H.-J., 2020, "Blødgøring af drikkevand: På vandværket eller hos forbrugerne?". Dansk Drikkevandskonference, Aarhus, Denmark, 18/11/2020.

Tang, C., Rosshaug, P.S., Kristensen, J.B., Merks, C.W.A.M., Rygaard, M., Albrechtsen, H.-J., 2019, "Optimal drinking water softening by the use of water quality indicators", EWA specialized workshop on treatment technologies for groundwater-based water supply, Copenhagen, Denmark, 9/5/2019.

Merks, C., **Tang, C.**, 2019, "Water softeners add comfort and cost water", IWA Efficient 2019, Manila, Philippines, 13/1/2019-16/1/2019.

Tang, C., Godskesen, B., Kristensen, J.B., Rosshaug, P.S., Albrechtsen, H.-J., 2018, Bedre forudsigelse af effekterne fra blødgøring, DANSKVAND 3, pp. 59

Tang, C., Albrectsen, H.-J., 2018, Blødgøring: Hvor meget kalk fjernes fra vandet? DANSKVAND 3, pp. 56-57

Tang, C., Hedegaard, M.J., Lee, C.O., Kristensen, J.B., Rosshaug, P.S., Lopato, L., Johansen, K.K., Merks, C., Albrechtsen, H.-J., 2018, "Optimering blødgøring med pelletmetoden – kalkfines og CCPP", Dansk Vand Konference, Aarhus, Denmark, 13/11/2018-14/11/2018.

Tang, C., Rosshaug, P.S., Kristensen, J.B., Albrechtsen, H.-J., 2018, "Holistic design of centralised drinking water softening", Nordic drinking water conference (NORDIWA), Oslo, Norway, 11/6/2018-13/6/2018.

Tang, C., Rosshaug, P.S., Kristensen, J.B., Rygaard, M., Albrechtsen, H.-J., 2018. Optimizing the benefits from drinking water softening by better calculating the calcium carbonate precipitation potential - CCPP. Danish Water Forum 12th Annual Water Research Meeting. Kongens Lyngby, Denmark, pp 30, 30/1/2018.

Tang, C., Albrechtsen, H.-J., Lopato, L., Kornholt, S.N., 2017, Pellets fra central blødgøring – fra affald til ressource. DANSKVAND 1, pp. 54-55.

Tang, C., Rosshaug, P.S., Kristensen, J.B., Rygaard, M., Albrechtsen, H.-J., 2017, "By-product reuse in drinking water softening: influence of operating conditions on calcium carbonate pellet characteristics" in 4th Water Research conference: The role of water technology innovation in the blue economy. Kitchener, Canada, 10/9/2017-13/9/2017.

Tang, C., Lopato, L., Kornholt, S.N., Albrechtsen, H.-J., 2017, "Possibilities for reuse of calcium carbonate pellets from drinking water softening" in Danish Water Forum 11th Annual Meeting. Copenhagen, Denmark, pp. 24, 30/1/2017.

Acknowledgements

I would like to thank my supervisors Professor Hans-Jørgen Albrechtsen and Associate Professor Martin Rygaard from DTU Environment, Planner Per Sand Rosshaug from HOFOR A/S, and Marked Director John B. Kristensen and Innovation Director Erik C. Wormslev from NIRAS A/S for your support and guidance throughout my PhD - it has truly shown the value of bringing academia, utility planning and engineering together.

Thanks to Cor Merks from Rambøll A/S for immense help with organizing my study trips to the Netherlands and always being available for questions.

Thanks to DTU Environment, NIRAS A/S and HOFOR A/S for financing the PhD.

I have had the pleasure of collaborating with Henrik Aktor from AA Water, Berit Godskesen from FORS, Marlies van Rijn formerly from Vitens, and Laure Lopato and Mathilde Jørgensen Hedegaard from HOFOR during my PhD. Thank you for sharing your expertise and feedback during the preparation of research papers. Thanks to Peter Borch Nielsen from Krüger for many professional discussions on softening and for letting me join the CARIX study trip.

Being able to see the practical applications of my PhD throughout the project has kept me highly motivated. Thanks to all of my colleagues at NIRAS A/S and especially team VAF2 for always making me feel welcome and as part of the team.

I would like to thank all my colleagues at DTU Environment, and especially the PhD group at the (former) Urban Water Systems section, for keeping my spirits up – even at a distance during the COVID-19 lockdown.

I am grateful to be surrounded by family and friends that always support me. Lastly, I would like to thank my husband Sebastian for help with preparing the graphics for my thesis, but most importantly for your never-ending support and for, together with Aksel, reminding me of what is truly important in life.

Summary

Drinking water utilities face increasing demands for drinking water that is not only safe and affordable, but also healthy and produced without negative environmental and societal impacts. Hard water contributes to consumer inconvenience by causing lime scaling in household installations and appliances, and by increasing soap use. Water softening is increasingly implemented to increase consumer convenience and can potentially provide socioeconomic and environmental benefits in areas with hard water. Although softening may appear as just a matter of removing hardness (i.e. Ca^{2+} and Mg^{2+}), softening technologies also change the overall mineral composition of the drinking water. If a process design for softening does not consider these changes, they may lead to adverse effects on e.g. human health and corrosion.

Indicators predict the effects from water quality changes and are used in decision support to evaluate the performance of technologies. However, the potential is still unexploited for using water quality indicators as decision support in implementation of softening. This PhD thesis builds on the hypothesis that by carefully selecting indicators and by considering the overall motivation for softening, the actual implementation can be optimized for local conditions, including source water quality. The hypothesis was investigated through a case study: implementation of softening in Denmark.

Historically, softening has been implemented to meet regulatory guidelines for mainly copper and lead, which can be released from pipe materials. Today, softening is predominantly implemented to increase consumer convenience, and softening has thereby shifted from being a “need to have” to a “nice to have” technology without a fixed guideline concentration as treatment objective. The softening technology which is the most suitable for reducing lead release from pipe materials may not be the best for reducing lime scaling in household appliances. Consequently, the overall treatment objective for softening should be clearly defined prior to designing the softening process to ensure that it is fit-for-purpose.

Decision support systems (DSSs) integrate various information and models to evaluate decision alternatives. In water treatment, DSSs often encompass technical, economic, environmental and social dimensions in a broad systems perspective. Unfortunately, the broad focus often reduces evaluation of water quality changes to removal of a single target compound (e.g. Ca^{2+}), which is

insufficient to evaluate the overall effects from softening on water quality. Decision support can be improved by expanding the traditional frameworks by evaluation of additional water quality indicators.

Softening is currently being implemented for the first time in Denmark to increase consumer convenience and provide socioeconomic and environmental benefits. If softening is not implemented centrally at the drinking water treatment plant, consumers may purchase decentralized softening units in their homes. Unfortunately, decentralized softening can result in increased water usage, lack of control with the drinking water quality, and can compromise the socioeconomic and environmental benefits from centralized softening.

The indicator Calcium Carbonate Precipitation Potential (CCPP) is important to include when implementing softening in Denmark. CCPP predicts the maximum potential for lime scaling in open (e.g. shower and kettle) and closed (e.g. distribution networks) systems. Other relevant indicators include corrosion indicators from the Danish Code of Practice (DS 439), investment and operating costs, building area/height requirements, by-product reuse possibilities (if pellet softening is implemented), wastewater quality and quantity, and magnesium removal for health reasons. Denmark is almost exclusively supplied by groundwater and many water utilities face recent findings of pesticides that threaten the drinking water quality. This should be considered when implementing softening by ensuring that the treatment process can be extended with pesticide removal or that hardness and pesticides are removed simultaneously by membranes.

The case study of softening in Denmark revealed that it is important to consider local conditions when evaluating softening scenarios. Water quality indicators provide valuable decision support, but also increase data requirements and analysis complexity. In practice, the level of information should be balanced to provide adequate decision support. This thesis has demonstrated that water quality is not only a technical issue but affects also human health, socioeconomy, the environment etc. Optimizing one aspect can result in suboptimal conditions in other aspects. In a given case, the best softening technology meets the treatment objectives and legislative guidelines, while balancing the remaining indicators to maximize the benefits from softening, identify possible adverse effects and support environmental and socioeconomic sustainability.

Dansk sammenfatning

Drikkevandsforsyninger står overfor øgede krav om at levere drikkevand, der ikke kun er sikkert og til at betale, men også er sundt og produceret uden negative konsekvenser for miljø og samfund. Hårdt vand er til gene for forbrugerne, da det medfører kalkudfældninger i husholdningsinstallationer og -apparater samt øger sæbeforbruget. Blødgøring bliver i stigende grad implementeret for at øge forbrugerkomforten og kan give samfundsøkonomiske og miljømæssige gevinster i områder med hårdt vand. Selvom blødgøring ser ud til blot at være et spørgsmål om at fjerne hårdhed (dvs. Ca^{2+} og Mg^{2+}), så ændrer blødgøringsteknologier den overordnede mineralsammensætning af drikkevandet. Hvis ikke disse ændringer inddrages, når man designer blødgøringsprocessen, kan blødgøring føre til uønskede effekter på f.eks. folkesundhed og korrosion.

Indikatorer kan forudsige effekterne af vandkvalitetsændringer og bliver brugt i beslutningsstøtte til at evaluere vandbehandlingsteknologier. Potentialet ved at bruge vandkvalitetsindikatorer som beslutningsstøtte ved implementering af blødgøring er imidlertid ikke fuldt udnyttet. Denne ph.d.-afhandlings overordnede hypotese var at ved at nøje udvælge indikatorer og klarlægge den overordnede motivation for blødgøring, kan den faktiske implementering bliver optimeret i forhold til lokale forhold, og herunder råvandskvalitet. Hypotesen blev undersøgt via en case: implementering af blødgøring i Danmark.

Blødgøring er historisk set blevet implementeret for at efterleve lovmæssige grænseværdier for især kobber og bly, der kan blive frigivet fra rørmaterialer. I dag bliver blødgøring primært implementeret for at øge forbrugerkomforten og har derfor skiftet fra en “need to have” til en “nice to have” teknologi, hvor der ikke findes en fastlagt målsætning for blødgøringsniveauet. Den blødgøringsteknologi, der er bedst egnet til at reducere frigivelse af bly fra rørmaterialer, er ikke nødvendigvis den bedste teknologi til at reducere kalkudfældninger i husholdningsapparater. Derfor bør den overordnede målsætning for blødgøring klart defineres inden processen designes for at sikre, at blødgøringsprocessen er bedst egnet til formålet.

Beslutningsstøttesystemer integrerer forskellig information og modeller for at evaluere beslutningsalternativer. I vandbehandling integrerer beslutnings-støttesystemer tekniske, økonomiske, miljømæssige og sociale dimensioner i et bredt systemperspektiv. Desværre reducerer det brede fokus ofte vandkvalitetsændringer til fjernelse af en bestemt kemisk forbindelse (f.eks. Ca^{2+}), hvilket ikke er tilstrækkeligt til at evaluere de overordnede effekter fra blødgøring. Beslutningsstøtte kan forbedres ved en integrering af yderligere vandkvalitetsindikatorer.

Blødgøring bliver i disse år implementeret for første gang i Danmark, og har til formål at øge forbrugerkomforten samt at give samfundsøkonomiske og miljømæssige gevinster. Hvis ikke blødgøring implementeres centralt på vandværket, kan forbrugerne selv købe decentrale blødgøringsenheder. Desværre kan decentral blødgøring medføre et højere vandforbrug, mangel af kontrol af drikkevandskvaliteten og kan kompromittere de samfunds-økonomiske og miljømæssige gevinster fra central blødgøring.

Kalkudfældningspotentialet (Calcium Carbonate Precipitation Potential, CCPP) er en vigtig indikator at inddrage ved implementering af blødgøring i Danmark. CCPP forudsiger det maksimale potentiale for kalkudfældninger i åbne (f.eks. brusebad og elkedel) og lukkede (f.eks. forsyningsnet) systemer. Andre relevante indikatorer er korrosionsindikatorer fra Dansk Standard (DS 439), investerings- og driftsomkostninger, krav til bygningsareal/-højde, genanvendelsesmuligheder for restprodukter (hvis pelletblødgøring implementeres), spildevandskvalitet og -kvantitet og fjernelse af magnesium af sundhedsmæssige årsager. Danmark er næsten udelukkende forsynet af grundvand og mange vandforsyninger står pt. overfor udfordringer med nylige fund af pesticider, der truer drikkevandskvaliteten. Dette bør der tages højde for i implementering af blødgøring ved at sikre, at vandbehandlingsprocessen kan udvides med fjernelse af pesticider eller ved at lade membranbehandling reducere hårdhed og pesticider samtidigt.

Casen om blødgøring i Danmark viste, at det er vigtigt at tage højde for lokale forhold, når man evaluerer blødgøringsscenarier. Vandkvalitetsindikatorer giver værdifuld beslutningsstøtte, men øger også databehovet og analysekompleksiteten. I praksis skal niveauet af information afbalanceres for at opnå tilstrækkelig beslutningsstøtte. Denne ph.d.-afhandling demonstrerede, at vandkvalitet ikke kun er et teknisk anliggende, men også påvirker folkesundhed, samfundsøkonomi, miljø m.m. Den bedste teknologi i en given case lever op til den overordnede målsætning og lovmæssige grænseværdier, og balancerer samtidigt de øvrige indikatorer for at maksimere gevinsterne ved blødgøring, identificere potentielle negative effekter og understøtte miljømæssig og samfundsøkonomisk bæredygtighed.

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Abbreviations

AHP	Analytical Hierarchy Process
BET	Brunauer-Emmett-Teller
Ca^{2+}	Calcium
$CaCO_3$	Calcium Carbonate
CARIX®	CArbon dioxide Regenerated Ion eXchanger
CCPP	Calcium Carbonate Precipitation Potential
Cl^-	Chloride
Cu	Copper
DANVA	Danish Water and Wastewater Association
° dH	German hardness degrees
DMF-S	Decayed, Missing and Filled tooth Surfaces
DSS	Decision Support System
DWTP	Drinking Water Treatment Plant
HCO_3^-	Bicarbonate
HOFOR	Greater Copenhagen Utility
K^+	Potassium
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
Mg^{2+}	Magnesium
Na^+	Sodium
NaCl	Sodium chloride
PAS	Plastic Air Softening
Pb	Lead
PHREEQC	pH-REdox-EQuilibrium in C
SDGs	Sustainable Development Goals
SEM	Scanning Electron Microscope
SO_4^{2-}	Sulphate

1 Introduction

Safe drinking water without harmful contaminants is essential to human life. Although it is still the main responsibility of water utilities to provide their consumers safe and affordable drinking water, today they face new demands for water that is also healthy in terms of its mineral composition (WHO, 2017), and produced without negative environmental or societal impacts. Drinking water softening is increasingly implemented to meet these demands (Mons et al., 2007a).

Hard water (i.e. with high concentrations of calcium, Ca^{2+}, and magnesium, Mg^{2+}) causes lime scaling in e.g. showers and kettles that must be removed by descaling agents and can reduce the service lifespan of household appliances and installations (Godskesen et al., 2019; Ragan et al., 2000; WHO, 2017). Softening can increase consumer convenience by reducing the negative effects from hard water, which can also provide socioeconomic and environmental benefits (Beeftink et al., 2021; Godskesen et al., 2012; van der Bruggen et al., 2009). Thus, softening may appear as an obvious addition to existing water treatment schemes in areas with hard water.

Unfortunately, the decision of implementing softening raises a number of questions with no simple answer related to the choice of technology and its design. Softening covers an array of technologies all with different design options (Ruhland and Jekel, 2004, Tang et al. **I**), resulting in many scenarios for implementation of softening. In addition to selecting the technology and its design, the softening depth (i.e. hardness removal) must be decided. Removing all hardness results in water that is calcium carbonate ($CaCO_3$) dissolving (aggressive), which can lead to corrosion in e.g. cement and iron pipes (Loewenthal et al., 2004). Moreover, soft water may become corrosive when mixed with other water types in the distribution networks (Imran et al., 2006). Softening removes not only hardness, but alters also the overall mineral composition of the drinking water (Ruhland and Jekel, 2004), and may therefore affect additional ionic species related to corrosion in the distribution networks (Edwards et al., 1996; Imran et al., 2006; Loewenthal et al., 2004) or minerals essential to human health (WHO, 2017).

Only few countries have maximum drinking water guideline concentrations for water hardness (Kozisek, 2020). Thus, unlike other water treatment technologies implemented to reduce specific ions and contaminants to below a specific guideline concentration, softening is predominantly implemented for optimization purposes. If the overall changes to water quality are not considered when designing the softening process and deciding the softening depth, softening can lead to adverse effects on human health and corrosion.

Indicators are used in decision support to e.g. estimate effects from water quality changes (Rygaard et al., 2011) and evaluate the performance of water treatment technologies (Hajkowicz and Collins, 2007; Hamouda et al., 2009), making them suitable for evaluating drinking water softening scenarios. However, the use of indicators to evaluate softening technologies, their design options and overall effects on water quality has been sparse. Studies have included only a limited number of technologies and focused primarily on technical and economic aspects (Bergman, 1995; Ruhland and Jekel, 2004; Thompson and Azar, 1999), have not considered the effects experienced by the consumers when evaluating the environmental impacts (Sombekke et al., 1997) or focused only on the environmental impact (Beeftink et al., 2021).

Water quality indicators can predict the effects from water quality changes on e.g. corrosion and human health and can thereby provide additional information on the potential benefits, but also potential adverse effects, from drinking water softening. Local conditions are important to include in the evaluation of softening scenarios. The source water quality may decide the best technology (Mons et al., 2007a), but other aspects such as legislative restrictions, building restrictions, possibilities for wastewater discharge, and reuse of by-products may also affect the best choice of technology. A framework for evaluating softening technologies that includes their overall effects on water quality and considers local conditions is lacking. Socioeconomic and environmental indicators should be integrated in such framework when evaluating softening scenarios to ensure that the implementation of softening is beneficial to society and thereby meets the sustainability agenda of today.

Considering local conditions, including the source water quality, can optimize decision support and enable water utilities to make informed decisions when implementing softening where the benefits and potential adverse effects that require preventive measures have been identified. This can ultimately lead to implementation of softening that is fit-for-purpose without compromising human health and with environmental and societal benefits.

1.1 Research questions

This PhD thesis builds on the hypothesis that by carefully selecting indicators and by considering the overall motivation for softening, the implementation of softening can be optimized for local conditions, including source water quality.

The hypothesis was examined through the following research questions:

1) How can the overall motivation for softening be used in formulating quantifiable treatment objectives to provide decision support when implementing softening?
2) What is an optimal softening technology?
3) How can we evaluate softening technologies using water quality indicators?
4) How can local conditions in a case study be included in the selection of indicators and evaluation of softening scenarios?

1.2 Methodology

Research questions 1 and 2 were primarily investigated by studying scientific literature. Tang et al. **I** provided a framework for evaluating and comparing softening technologies using water quality indicators, which was used to answer research question 3 and 4. Implementation of softening in Denmark was selected as case study to investigate how local conditions affect decision support when implementing softening. The case study was furthermore chosen to investigate the practical applications of the decision support framework proposed in this thesis and discuss its possibilities as well as limitations.

The study of scientific literature focused primarily on the following topics:

- The motivation for softening, expanding the literature review of Mons et al. (2007a) with additional literature from 2007 and onwards
- Decision support systems in drinking water treatment
- Water quality indicators (for more details see Tang et al. **I** and Tang et al. **III**)
- Decentralized softening (for more details see Tang et al. **II)**
- Softening in Denmark, which was supported by my personal experience from the engineering consultancy NIRAS A/S

The following methods were used to investigate water quality indicators, and the effects of source water quality and seeding material on the characteristics of pellets from pellet softening:

- PHREEQC (pH-REdox-Equilibrium in C) modelling to calculate the Calcium Carbonate Precipitation Potential (CCPP, Tang et al. **III**) and model the chemical speciation during pellet softening (Tang et al. **IV**).
- Design of pellet softening pilot-scale investigations with different seeding material at Frederiksberg drinking water treatment plant (DWTP)
- Various laboratory analyses of pellets including the Brunauer–Emmett–Teller (BET) surface area, X-ray diffraction and Scanning Electron Microscope (SEM) images.

2 Motivation for drinking water softening and its role in decision support

Softening can be implemented for several reasons that can affect which technology is the best in a given case. This chapter explores the different drivers for softening and how defining the overall treatment objective(s) can provide decision support when implementing softening.

2.1 Reasons for implementing softening

Softening reduces water hardness and has historically been implemented for several reasons (Figure 1).

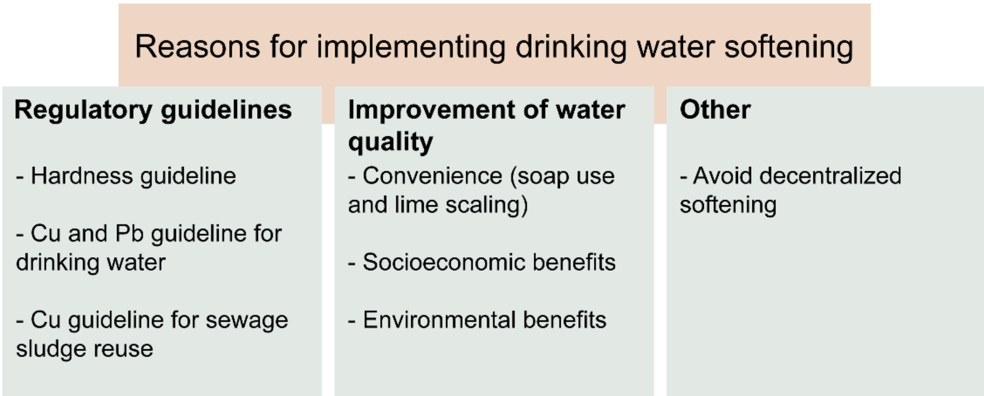

Figure 1: Reasons for implementing drinking water softening grouped by regulatory guidelines ("need to have"), improvement of water quality ("nice to have") and others.

Mons et al. (2007) reviewed the motivation for centralized softening and argued that "source water quality will determine what softening technology is best to be used" (Mons et al., 2007a). In the following I summarize the different reasons for softening with focus on recent literature (> 2007) and argue that the best softening technology depends not only on the source water quality, but also on the motivation for implementing softening.

2.1.1 Compliance with regulatory guidelines

In 1998, Ca^{2+}, Mg^{2+} and hardness were excluded from the European Commission Drinking Water Directive (Kozisek, 2020). The revised Drinking Water Directive from 2020 states that "where water intended for human consumption is derived from treatment that significantly demineralizes or softens water, calcium and magnesium salts could be added to condition the water in order to reduce any possible negative health impact, as well as to reduce the corrosiveness or aggressiveness of water and to improve taste…”, but it does not provide neither maximum nor minimum concentrations of Ca^{2+} and Mg^{2+} (The Council of the European Union, 2020). Today, 12 member states still include the hardness ions in their national legislation or in technical standards, although nine only include hardness ions as indicator parameters of less importance than actual guideline concentrations (Kozisek, 2020). The hardness ions can be regulated either as maximum levels (Ca^{2+}: 100-270 mg/L and Mg^{2+}: 30-125 mg/L) or minimum levels after softening (total hardness: 0.9-1.5 mmol/L, 5-8.4 °dH) (Kozisek, 2020).

Another reason for implementing softening is to reduce the concentrations of lead (Pb) and copper (Cu) in drinking water to below the guideline concentrations (10 µg/L for Pb, 5 µg/L from 2036, and 2 mg/L for Cu) (The Council of the European Union, 2020). Pb and Cu may be released into the drinking water by corrosion from distribution pipes and household plumbing. In 1993, the WHO proposed a new guideline for Pb lowering it from 50 µg/L to 10 µg/L. In 1998, the Pb guideline concentration drinking water was lowered to 10 µg/L in the Drinking Water Directive effective by 2013 (SCHER, 2011). Hard water with high alkalinity has low pH that can accelerate Pb corrosion (Mons et al., 2007a). In order to meet the new guideline concentration, centralized softening was implemented in e.g. the Netherlands to reduce Pb release from distribution pipes, until pipes eventually were replaced by other materials (van den Hoven et al., 1998).

Cu can similarly be released from pipe materials into the drinking water and ends up in either effluent water or sewage sludge from wastewater treatment plants. The concentration of Cu in sewage sludge may limit the reuse possibilities for soil improvement in agriculture, thereby motivating softening (Mons et al., 2007a).

2.1.2 Improvement of water quality

Nowadays, a main driver for implementing softening is to increase consumer convenience (Mons et al., 2007a, Figure 1). This development reflects a shift from softening being necessary to comply with existing legislation (“need to have”) to being a tool for optimizing water quality (“nice to have”). In areas with hard drinking water, water softening can provide:

- Decreased use of detergents, descaling agents and soap (Godskesen et al., 2019; WHO, 2017)

- Decreased energy use of household appliances, installations and water heaters (Godskesen et al., 2019)
- Potentially increased service life span of household appliances, installations and water heaters (Abeliotis et al., 2015; Ragan et al., 2000), although the correlation between water hardness and expected lifespan of appliances has only little attention in literature
- Reduced work load removing limescale from e.g. bathroom tiles (Godskesen et al., 2012)

In addition to the experienced consumer convenience, the reduced soap and detergent use as well as reduced lime scaling can also result in socioeconomic benefits (van der Bruggen et al., 2009), although a Danish study indicated that industries with a high water usage and decentralized softening may experience higher overall costs (Rambøll, 2017, Section 4.2).

Finally, softening can lead to environmental benefits in terms of reduced carbon footprint (Beeftink et al., 2021) and other impact categories such as human toxicity, global warming potential and resource consumption (Godskesen et al., 2012).

The environmental benefits from implementing softening can also include reduced use of detergents and phosphates as corrosion inhibitors that can be a threat to the aquatic environment if not removed sufficiently during wastewater treatment (Mons et al., 2007a). Pellet softening produces a solid by-product (pellets) that may be reused in industry and can potentially substitute virgin materials depending on their content of impurities (Tang et al. **IV**, Section 4.4.3).

2.1.3 Other reasons

Drinking water utilities may also implement centralized softening (i.e. at the DWTP) to reduce the number of decentralized softening units (i.e. in e.g. private households) that can result in chloride (Cl^-) pollution (Bakshi et al., 2021) and pose a health risk from microbial growth if the softening units are not maintained properly (Mons et al., 2007a). Decentralized softening compared to centralized softening is further addressed in Section 4.3.

2.2 What is soft water?

2.2.1 Hardness classification

In practice, drinking water hardness is defined as the sum of Ca^{2+} and Mg^{2+} concentrations (Loewenthal and Marais, 1976). Other multivalent ions may contribute to the water hardness, but in drinking water they are often present in much lower concentrations and therefore with a limited contribution to total hardness (de Moel et al., 2006; Nazaroff and Alvarez-Cohen, 2001). In this thesis, water hardness is reported in mmol/L and German hardness degrees (1 °dH = 0.18 mmol/L).

Softening technologies reduce the concentrations of Ca^{2+} and potentially also Mg^{2+} in the drinking water (Tang et al. **I**), resulting in "softer" water. Despite the clear definition of water hardness, the classification of "soft" and "hard" drinking water varies internationally (Figure 2). Rygaard and Albrechtsen (2020) compiled the classification of different hardness levels in Denmark, Sweden, the Netherlands, USA, Australia and UK. For instance, drinking water with a hardness of 1.2 mmol/L (7 °dH) is considered "soft" in Denmark and the Netherlands, but "moderately hard" in Sweden and UK, and even "hard" in USA (Figure 2).

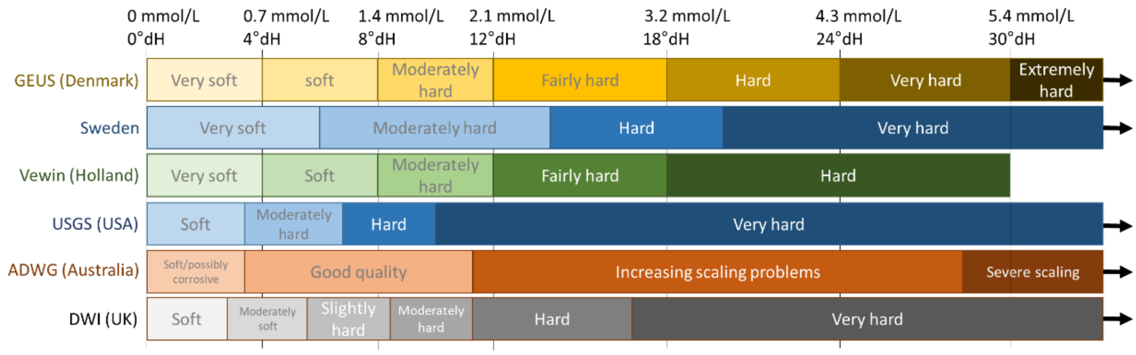

Figure 2: Different classifications of hardness levels adapted from Rygaard and Albrechtsen (2020).

Implementing softening to remove hardness from already "soft" water is somewhat conflicting. Therefore, the different classifications of "soft" and "hard" water across countries can result in different interpretation of when softening is relevant and consequently implementation of softening at different hardness levels.

2.2.2 Softening technologies

Softening covers an array of technologies that remove hardness by different mechanisms. These can be grouped into precipitation, ion exchange and membrane separation technologies (Tang et al. **I**). Some technologies can be applied for softening in small scale, decentralized softening e.g. in private households, whereas other technologies require special facilities and chemical handling making them only suitable for softening at larger scale centralized at the DWTP (Tang et al. **II**, Table 1). For a description of the technologies see Tang et al. **I** and **II**.

Table 1. Technologies for centralized and decentralized drinking water softening including their main mechanism for hardness removal. Adapted from Tang et al. II.

Hardness removal mechanism Technology	**Centralized softening**	**Decentralized softening**
Precipitation		
Pellet softening	X	
Lime/soda-ash softening	X	
Ion exchange		
Strong-acid cation exchange	X	X
Weak-acid cation exchange (CARIX® [1])	X	
Membrane separation		
Nanofiltration	X	
Reverse osmosis	X	X

[1] CARIX®: CArbon dioxide Regenerated Ion eXchanger

In addition to the technologies presented in Table 1, physical water conditioners are in the market that are not designed for hardness removal, but to alter the physical characteristics of minerals in the water and prevent lime scaling by e.g. magnetism or electrostatic forces (Georgiou et al., 2018). The mechanisms of these technologies are not fully understood and the effects on e.g. use of soap and descaling agents have not been demonstrated in literature (Tang et al. **II**). Consequently, physical water conditioners are not considered further in this thesis that focuses solely on technologies that remove hardness from the water (Table 1).

Softening is implemented centrally in different parts of the world. In France, < 5 % of the drinking water is softened (Mons et al., 2007a). > 1000 DWTPs have implemented softening in the U.S. corresponding to about 13 % of the total drinking water production (Mons et al., 2007a). In the Netherlands about 50 % of the drinking water is softened centrally (Hofman et al., 2007).

Each softening technology comes with a variety of design options. Pellet softening can e.g. be designed with different seeding material (quartz/garnet sand or crushed pellets), base chemical (sodium or calcium hydroxide) and can be implemented in different locations in a groundwater treatment train consisting of aeration and rapid sand filtration (before/after aeration or after rapid sand filtration) (Schetters et al., 2015; van Dijk and Wilms, 1991). Consequently, drinking water utilities face multiple scenarios in terms of technology choice and process design when implementing softening, which complicates decision making.

2.3 Defining the treatment objective(s) for softening

Softening can be implemented for regulatory, aesthetic, environmental and socioeconomic reasons (Section 2.1). By identifying the main driver(s) for implementing drinking water softening, treatment objectives can be defined. This is often the first step in existing DSSs for design of water treatment (Hamouda et al., 2009; Saaty, 2008), but is yet to be applied in softening.

Rephrasing the drivers for implementing softening from Section 2.1 could result in specific treatment objectives such as:

a) Observably reduce lime scaling in household appliances and installations (to increase consumer convenience)

b) Reduce the Mg^{2+} concentration to < 50 mg/L (to meet regulatory guidelines)

c) Reduce the concentration of Pb in drinking water by the consumers' tap to < 10 µg/L (to meet regulatory guidelines)

The softening technology that is the best for reducing the Pb concentration in drinking water, may not also be the best for increasing consumer convenience, and technologies that improve water quality in one aspect may have adverse effects in others (Tang et al. **I**). Although, treatment objectives do not translate directly into decision making, they can form the basis for selecting criteria for further evaluation (Hamouda et al., 2009) and support that the chosen softening technology is fit-for-purpose.

Summary

- The drivers for implementing softening are multiple and include regulatory guidelines as well as aesthetic, economic and environmental aspects. Nowadays, softening is often implemented to increase consumer convenience, which has shifted softening from being a “need to have” to a “nice to have” technology.
- Softening technologies remove hardness by different mechanisms (precipitation, ion exchange and membrane separation) and can be designed in multiple ways, resulting in many possible softening scenarios.
- By clearly defining the motivation for softening, treatment objectives can be formulated that can support design of a softening process that is fit-for-purpose.

3 Indicators in decision support

The motivation for implementing softening can be expressed in one or more treatment objective(s) (Section 2.3). However, typically a number of additional criteria apply when selecting a treatment technology including costs, environmental sustainability, compliance to regulatory guidelines, social acceptance etc. making the selection multi-objective (Hajkowicz and Collins, 2007; Hamouda et al., 2009). Moreover, several softening technologies exist with a number of design options resulting in many scenarios (Tang et al. **I**, Section 2.2.2). Finally, the effects from softening must be evaluated before the technology is implemented. All of the above contribute to increasing decision complexity.

Indicators predict the effects from drinking water treatment and are used in decision support to evaluate criteria covering different dimensions (Hajkowicz and Collins, 2007; Hamouda et al., 2009). In this chapter, I introduce two frameworks for evaluating softening technologies using indicators including their possibilities and weaknesses. I distinguish between a “broad” evaluation, aiming to encompass technical, economic, environmental and economic dimensions, and a “deep” evaluation aiming to go into depth with a single aspect, in this case water quality.

3.1 Decision support systems

DSSs are designed “to integrate various information (quantitative and qualitative) and models to analyse and compare decision alternatives” (Zhang et al., 2013), thereby supporting decision making in complex and multi-objective problems such as the implementation of softening.

DSSs often aim to analyse the different scenarios in a “broad” systems perspective including at least technical and economic dimensions, but often also environmental and social dimensions as well (Figure 3) (Godskesen et al., 2018; Hamouda et al., 2009).

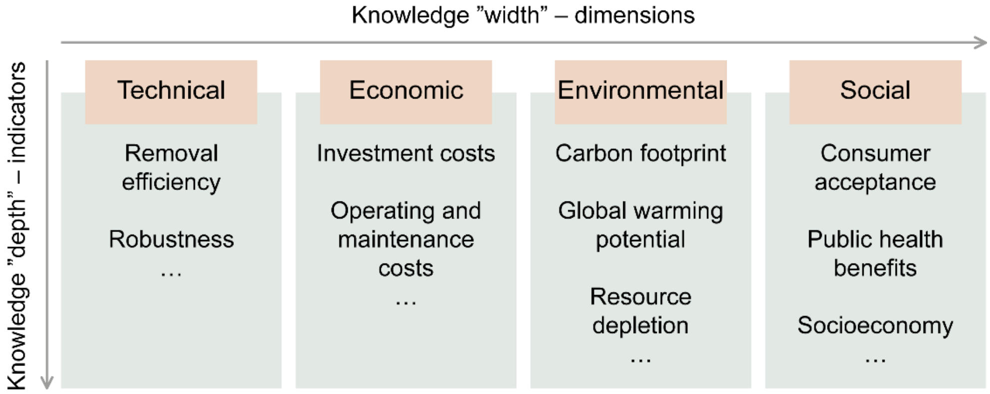

Figure 3: Dimensions included in "broad" DSSs and examples of indicators within each dimension

Within each dimension, indicators are selected to evaluate the effects using mathematical decision support models such as multi-criteria decision analysis (MCDA) and analytical hierarchy process (AHP) (Hajkowicz and Collins, 2007; Hamouda et al., 2009; Saaty, 2008). The choice of indicators greatly affects the outcome of the evaluation (Hajkowicz and Collins, 2007; Hamouda and Huck, 2010), and often experts and stakeholders are involved in choosing and weighing indicators (Godskesen et al., 2018; Hamouda and Huck, 2010). DSSs have been developed for both design and operation of drinking water treatment (Hamouda et al., 2009; Zhang et al., 2013), but the potential for use of DSSs in water softening is unexploited. Only few studies compare softening scenarios with costs and technical indicators being the main focus (Table 2).

Table 2. Literature studies evaluating and comparing various drinking water softening technologies.

Reference	Technologies	Method	Comments
Bergman (1995)	Lime softening and nanofiltration	Cost comparison	Color and dissolved organic carbon removal were included in addition to hardness removal
Sombekke et al. (1997)	Pellet softening and nanofiltration	MCDA and life cycle assessment	Did not consider consumer effects
Thompson and Azar (1999)	Lime softening, ion exchange, nanofiltration and reverse osmosis	Evaluation of 7 alternatives using MCDA	Criteria included technical and economic aspects only
Ruhland and Jekel (2004)	Lime softening, pellet softening CARIX® and nanofiltration	Multiple indicators	Mainly technical and economic. Environmental indicators were not quantified.
(Beeftink et al., 2021)	Pellet softening, membrane separation, ion exchange	Life cycle assessment	Only environmental dimension

Evaluation of softening technologies in a DSS framework allows for multiple criteria and can provide decision support that is beyond an assessment of hardness removal and costs (Tang et al. **II**).

A weakness of existing DSSs is the relatively large data requirements and resources required for building up as well as maintaining a database. Consequently, very few DSSs for water treatment systems exist on the market as commercial products (Hamouda et al., 2009). Moreover, a DSS framework with only few indicators within each dimension and with "removal efficiency" being the primary indicator for water quality changes may overlook adverse effects from softening and may not be sufficient for evaluating if the treatment objective has been met.

3.2 Diving into water quality

Softening alters the overall mineral composition of drinking water, which can lead to a broad range of effects on e.g. corrosion, human health, lime scaling etc. (Tang et al. **I**). Tang et al. **I** proposed a framework for evaluating softening technologies based on water quality indicators (Figure 4), which has not previously been established in literature.

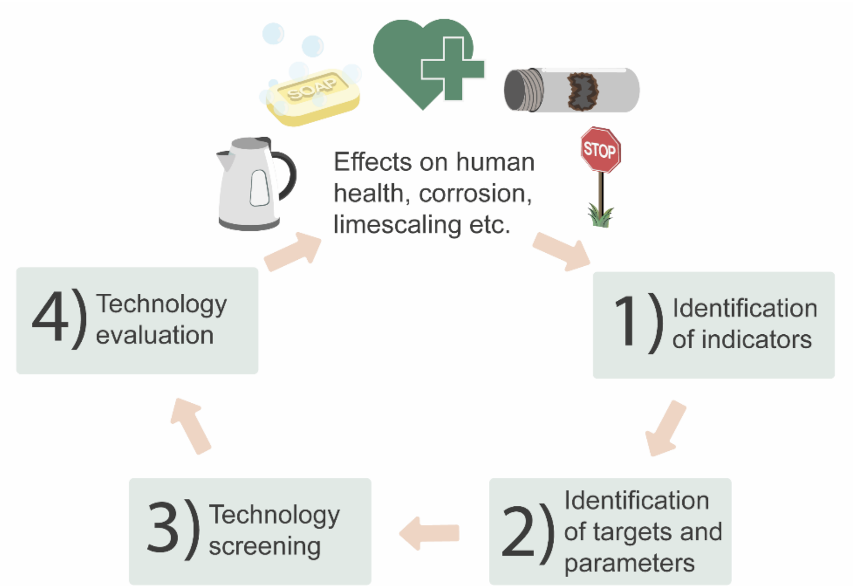

Figure 4: Framework for evaluating and comparing softening technologies based on water quality indicators (Tang et al. I).

Water quality indicators can predict effects from softening and quantify the treatment objectives. If softening is implemented to reduce Pb release from pipe materials, Pb release can be predicted from the water temperature, alkalinity, pH, Cl^- and sulphate (SO_4^{2-}) concentrations (Imran et al., 2006).

The precipitation technologies all decrease Pb release, since they remove alkalinity and increase pH, whereas the effects from membrane separation and weak-acid cation exchange depend on the source water quality and process design (Tang et al. **I**).

If, on the other hand, the main treatment objective is to reduce lime scaling in household appliances and installations, the indicator CCPP is currently the most accurate to predict this (Tang et al. **III**). The CCPP is defined as the amount of $CaCO_3$ that theoretically can precipitate or dissolve from water in order to reach equilibrium with solid $CaCO_3$ (Rossum and Merrill, 1983), and predicts the maximum potential for lime scaling in closed (e.g. distribution networks) and open (e.g. shower) systems at different temperatures (Tang et al. **III**). All softening technologies reduce the CCPP by removing Ca^{2+} and potentially also alkalinity from the water (Tang et al. **I**), but by how much depends on the technology, its design and the overall treatment train (Tang et al. **II**).

Although water quality changes typically are considered within the technical dimension in DSSs (Hamouda and Huck, 2010; Jones et al., 2019; Sadr et al., 2020), the effects predicted by water quality indicators also affect the other dimensions (Figure 5).

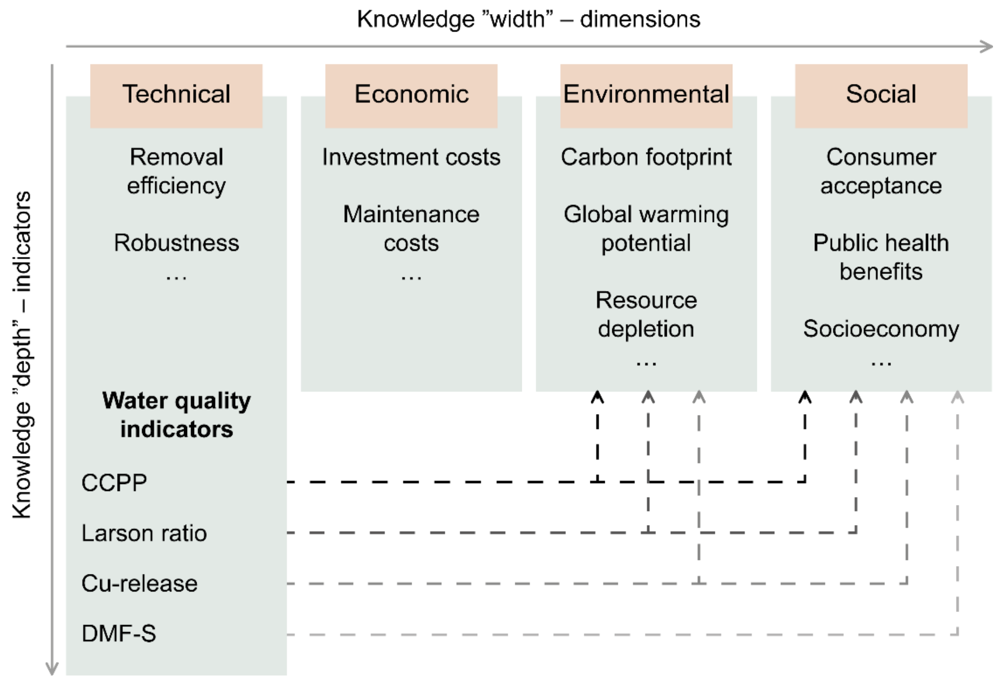

Figure 5: Water quality indicators are typically considered technical, but affect also e.g. environmental and social dimensions.

Reducing the CCPP increases consumer convenience (Brink et al., 2004), but also potentially reduces the carbon footprint (environment) and costs (society) from reduced use of descaling agents and prolonged lifespan of appliances (Beeftink et al., 2021; van der Bruggen et al., 2009). On the contrary, Arvin et al. (2017) found indications that reducing Ca^{2+} in drinking water may increase caries prevalence in the population (indicator Decayed, Missing, Filled tooth Surfaces, DMF-S), thereby resulting in adverse socioeconomic and public health effects (Figure 5). Similarly, corrosion indicators such as the Larson Ratio and Cu release predict effects also related to socioeconomy (from e.g. pipe repair costs) and environment (from e.g. release of Cu into wastewater sludge) (Figure 5).

Knowledge on the overall water quality changes from softening is required to calculate water quality indicators (Tang et al. **I**). However, diving into water quality can improve decision support and increase knowledge on the technical, economic, environmental and societal effects from softening.

3.2.1 Challenges associated with water quality indicators

Several challenges are associated with the use of water quality indicators for evaluating and comparing softening technologies, including:

Lack of well-documented indicators to quantify effects: Drinking water taste affects the consumers' aesthetic perception of the water (Platikanov et al., 2013), however, no indicator is currently available for assessing drinking water taste since this is relative and subjective (Lahav and Birnhack, 2007). According to the WHO, consumers are likely to notice changes in hardness (WHO, 2017). Platikanov et al. (2013) identified ions with a positive (Ca^{2+}, Mg^{2+}, bicarbonate (HCO_3^-) and SO_4^{2-}) and with a negative (sodium (Na^+), potassium (K^+) and Cl^-) effect on taste using trained panellists, but the taste experience also depended on the overall mineral level in the water. The concentrations of the above ions may change during softening and affect water taste, but the effects cannot be quantified with an indicator (Tang et al. **I**).

Inconsistency in calculation methods for a specific indicator: Other indicators can be calculated using different methods resulting in inconsistency in values reported in literature. An example of this is the CCPP that is calculated using different standards, software, solubility data and ionic species (Tang et al. **III**). Reduction in lime scaling is a main driver for implementing softening (Section 2.1.2), but inconsistent calculation methods hamper the use of CCPP as an indicator to quantify this treatment objective. Tang et al. **III** proposed a unified method for calculating the CCPP in drinking water systems for overcoming this that also includes precipitation in open systems not previously considered in literature.

Lack of understanding of correlation between indicator and physical phenomena: Indicators are not ideal representations of the phenomena they predict and the observed effects may therefore vary from the predicted (Hamouda et al., 2009). This is the case for corrosion indicators, where the correlation between the chemical composition of drinking water and corrosion is still to be fully understood (Loewenthal et al., 2004; Lytle et al., 2020). The Pb release model suggested by Imran et al. (2006) must be adjusted to the historical Pb release and was found to overpredict the Pb release when compared to actual Pb release data (Imran et al., 2006). Likewise, CCPP represents a theoretical maximum potential for $CaCO_3$ precipitation or dissolution, but the actual (observed) lime scaling also depends on e.g. water flow velocity and surface characteristics (APHA/AWWA/WEF, 2017; MacAdam and Parsons, 2004). In order to improve the use of indicators when implementing softening, such research gaps must still be closed to evaluate the effects from softening as accurately as possible.

3.3 What makes the optimal softening technology?

A “broad” evaluation in a classic DSS framework can provide an overview of technical, economic, environmental, and societal effects from softening (Section 3.1). This can support decisions that e.g. maximize the environment benefits or meet the treatment objectives at the lowest possible costs. However, softening affects the overall mineral composition of water and may have adverse effects on e.g. human health and corrosion, if hardness removal is the only water quality indicator considered. Including a “deep” evaluation of relevant water quality indicators in a “broad” DSS framework will improve decision support by quantifying a range of potential effects from softening that vary depending on the technology (Tang et al. **I**). Thus, neither the “broad” nor the “deep” framework presented in this chapter should stand alone, but should be used in combination to optimize decision support.

Unfortunately, ideal implementation of softening with only positive effects on all indicators, while achieving the treatment objective, is impossible. For instance, if the overall motivation for implementing softening is to reduce lime scaling, the optimal process design would reduce the CCPP to 0 mmol/L at elevated temperatures and in open systems (i.e. $CCPP_{40, open}$ and $CCPP_{90, open}$), thereby providing consumers with a “spotless” bathroom and maximum convenience. However, a $CCPP_{90, open}$ of 0 mmol/L, would most likely result in a negative CCPP at lower temperatures and in closed systems (Tang et al. **III**), that may cause corrosion in cement and iron distribution pipes or be non-compliant with drinking water guidelines (Loewenthal et al., 2004).

Rosborg and Kozisek (2019) suggested optimal concentrations of various ionic species in drinking water from, primarily, a health perspective. The recommended concentrations for Cl^- (20-50 mg/L), SO_4^{2-} (25-100 mg/L) and HCO_3^- (100-300 mg/L) can in the most extreme case result in a Larson Ratio of 2.1 that would be corrosive towards stainless steel (Dansk Standard, 2009; Rygaard et al., 2011). This illustrates that a softening process design that is the optimal in one aspect, may be suboptimal in others.

Thus, the optimal softening technology meets the treatment objective while balancing the remaining effects in the most acceptable way. This necessitates multi-objective decision making that can handle multiple and sometimes conflicting indicators.

Summary

- Decision support for choosing softening technology is complex due to the many scenarios for implementing softening and multiple criteria in addition to the main treatment objectives.
- Existing DSS frameworks often aim at a “broad” evaluation encompassing technical, economic, environmental and social dimensions, but may overlook important effects from water quality changes if only few indicators are included within each dimension.
- Water quality indicators can estimate the effects from the different softening technologies and contribute to increased knowledge within the economic, environmental and social dimensions.
- The optimal softening technology fulfils the overall treatment objective and balances additional indicators within technical, economic, environmental and social dimensions, including the effects on water quality indicators.

4 Case study: Softening in Denmark

4.1 Drinking water infrastructure

In Denmark, drinking water is almost exclusively based on groundwater that is treated at about 2,600 DWTPs, which are either private or operated by water utilities (DANVA, 2020). However, many are small and 340 DWTPs account for 2/3 of the total amount of drinking water produced in Denmark (DANVA, 2020; Miljøstyrelsen, 2021). Groundwater treatment in Denmark is characterized as "simple" consisting of aeration and rapid sand filtration. In the annual statistics of the Danish Water and Wastewater Association (DANVA), drinking water utilities supplying a total of 3.4 million people or 59 % of the Danish population are represented with data. Of the 218 DWTPs with reported water hardness, most (115) deliver fairly hard water (Figure 6) based on the Danish hardness classification (Figure 2). A few (32), but large, DWTPs deliver hard or extremely hard drinking water (Figure 6) and implementing softening at these would supply 18 % of the Danish population with softer water.

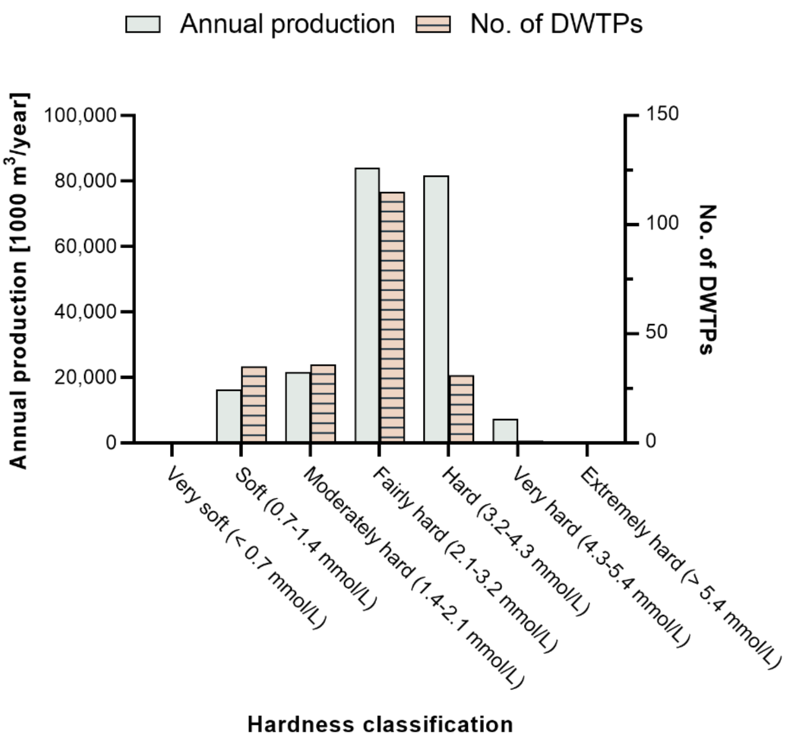

Figure 6: Overview of DWTPs in Denmark and their annual production [m^3/year] sorted by reported water hardness. Data from DANVA (2020).

Until 2016, drinking water was not softened neither centrally at DWTPs nor decentralized in private households in Denmark. Today, softening is increasingly implemented, mainly for two reasons:

1. The Greater Copenhagen utility (HOFOR) decided to gradually implement centralized softening as part of modernization of their seven regional DWTPs, thereby supplying about 1 million consumers in the Copenhagen area with softer water from approx. 2028 (HOFOR, 2021a).
2. New legislation was passed in 2016 permitting decentralized softening units in contact with drinking water to be sold and installed in Denmark if they are certified by either Danish, Dutch, Swedish or German drinking water certification (Transport- og Boligministeriet, 2016).

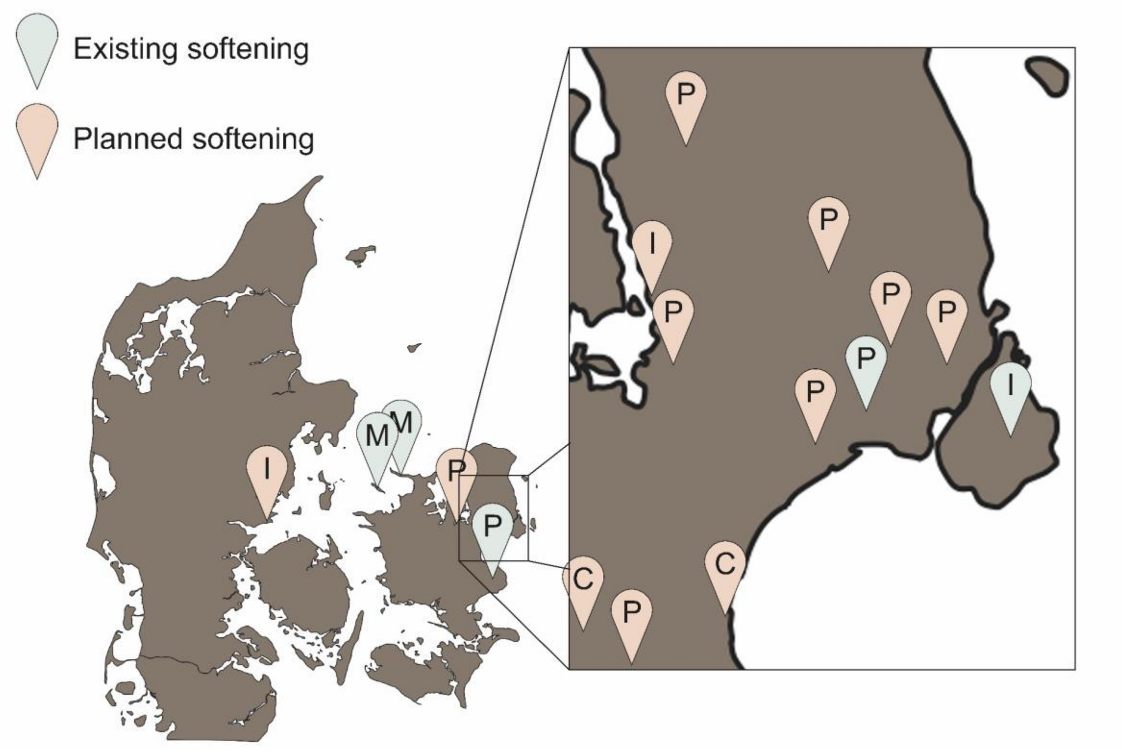

Figure 7: DWTPs in Denmark with existing or planned drinking water softening. I = ion exchange, P = pellet softening, C = CARIX® and M = membrane separation. (Frederiksberg Forsyning, 2021; HOFOR, 2021a; Juelsminde Vand, 2021; Nielsen, 2021; Solrød Vandværk, 2021; St. Heddinge Vandværk A.m.b.a., 2021)

In 2017, softening was implemented centrally at Brøndbyvester DWTP operated by HOFOR (pellet softening), at the private DWTP St. Heddinge (pellet softening) and at Tårnby DWTP operated by Tårnby Forsyning (strong-acid cation exchange) (HOFOR, 2021a; St. Heddinge Vandværk

A.m.b.a., 2021; Tårnby Forsyning, 2021). The two DWTPs Sejerø operated by Kalundborg Forsyning and Yderby Lyng have implemented reverse osmosis for desalination of brackish groundwater that also softens the water (Nielsen, 2021). From 2021 and onwards, pellet softening, strong-acid ion exchange and CARIX® softening are planned in Denmark (Figure 7).

More drinking water utilities are expected to consider softening and may decide to implement softening centrally. They will have to decide on the softening technology, softening depth and process design. In the following, I investigate how the motivation for softening in Denmark and specific, local conditions can lead to a selection of relevant indicators that can optimize decision support.

4.2 Motivation for softening in Denmark

In Denmark, the drinking water hardness varies from soft (0.7-1.4 mmol/L, 4-8 °dH) to extremely hard (> 5.4 mmol/L, > 30 °dH) (GEUS, 2010). Drinking water is hardest in the Eastern part of Denmark, which is also where softening already has been implemented (Figure 7). Denmark has no guideline concentration or recommendation for water hardness (Miljø- og Fødevareministeriet, 2019a), so the driver for softening is not from regulatory requirements.

When new EU legislation was passed in 1998 reducing the guideline concentration for Pb to 10 µg/L, the majority of Pb pipes had already been replaced by other materials in Denmark (Buus, 1998), except for few cases (Adolfsen, 2014; Petersen, 2011). The Danish "Code of practice for domestic water supply systems" (DS 439) only mentions Pb a single time (Dansk Standard, 2009), also illustrating the Pb release from drinking water pipes and installations is not a major issue in Denmark, although it may be released from e.g. fixtures. If Pb piping had not already been replaced, drinking water softening might have been implemented in Denmark in the 1990's to reduce Pb release, similarly to the development in the Netherlands.

The implementation of softening in Denmark is primarily driven by consumer convenience, but also by socioeconomic and environmental benefits, and is hence driven by a wish to improve water quality (Figure 1). Several studies have evaluated the socioeconomic effects from centralized softening in Denmark or specific water utility supply areas (Cowi, 2011; Deloitte, 2015a, 2015b; Rambøll, 2017). The most recent study from Rambøll concluded that softening provides socioeconomic benefits for private households if the water hardness is reduced to 2.5 mmol/L (14 °dH) in Eastern Denmark (on Funen and most of Zealand) and is reduced to 1.1 mmol/L (6 °dH) in parts of Western Denmark with fairly hard water (parts of Jutland) (Rambøll, 2017). However, the study did not consider if it is technically feasible to reduce the water hardness to 1.1 or 2.5 mmol/L. Industries with high water usage and decentralized softening will often still need to soften the water to 0 mmol/L for their processes, but will experience higher water prices if centralized softening is implemented. Consequently, their overall expenses may increase as a consequence of centralized softening. Nonetheless, the potential benefits for private households exceed these resulting in overall socioeconomic benefits (Rambøll, 2017).

The Danish water utilities have increasingly focus on sustainability (DANVA, 2020). For instance, HOFOR has an aim of a 100 % CO_2 neutral drinking water supply by 2025 (HOFOR, 2021b), and Aarhus Vand supplying Aarhus, the second largest city in Denmark, with drinking water has been certified in the sustainable development goals (SDGs) (Aarhus Vand, 2021). Due to the increased sustainability focus, a softening process design with an overall negative environmental impact is likely to be unacceptable for Danish water utilities. Godskesen et al. (2012) evaluated the environmental impact from drinking water softening in the Copenhagen area using life cycle assessment (LCA) and concluded that the break-even softening depth where centralized softening with pellet softening (sodium hydroxide) becomes environmentally beneficial is at only 0.2 mmol/L (1.2 °dH), illustrating that softening has the potential for providing environmental benefits.

Thus, when implementing softening in Denmark it is important to evaluate indicators that reflect consumer convenience, while ensuring that the softening provides both socioeconomic and environmental benefits.

4.3 Centralized vs. decentralized softening

Softening can either be implemented centralized at the DWTP or decentralized at individual household/housing association level (Tang et al. **II**, Figure 8). Especially strong-acid cation exchange with sodium chloride (NaCl) regeneration is commonly used for decentralized softening (Bakshi et al., 2021; Mons et al., 2007b; van der Bruggen et al., 2009) and is the main focus in this section.

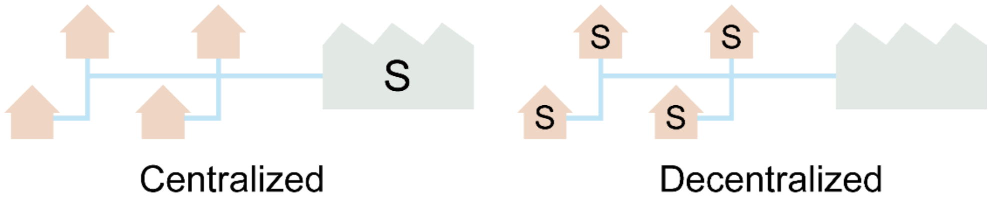

Figure 8: Centralized softening at the DWTP vs. decentralized softening at the individual households.

No overview exists of the prevalence of decentralized softening units. Among 18,500 residents in the Flemish region Heers-Gingelom that receive drinking water with a hardness of 4.7-5.0 mmol/L (26-28 °dH), 36 % owned a decentralized softening unit (van der Bruggen et al., 2009). In Minnesota, USA, 75 % of the population receive hard drinking water produced from groundwater (2.5 - > 5.0 mmol/L, 14 - > 28 °dH) and 72 % of all households have decentralized softening units (Bakshi et al., 2021), indicating that decentralized softening is widespread in parts of the world.

In Denmark, private decentralized softening units are not required to be registered and their prevalence is unknown. In a user survey among 2,485 households (46 % reply rate) in the supply area of the private DWTP Solrød Vandværk, 8 % of households had a decentralized softening unit installed and 49 % had considered installing decentralized softening (Solrød Vandværk, 2020). Although the survey from Solrød Vandværk only represented a small group of households in an area with hard water (3.7 mmol/L, 21 °dH), it indicates an interest in decentralized softening in Denmark emphasizing that consumers want softer drinking water.

Decentralized softening enables consumers to experience the increased convenience from softer water in areas where centralized softening has not been implemented, but has several drawbacks compared to centralized softening:

Higher water usage: All softening technologies use water as part of the process. For instance, water is used for regeneration of the ion exchange resin and membrane separation produces retentate containing all the rejected ions. Although the water usage varies depending on the technology, some decentralized softening technologies have a water usage > 100 % of the produced amount of water (Tang et al. **II**). This water usage is beyond the control of the drinking water utility, and even an additional water usage of a few percent may lead to exceedance of groundwater abstraction limits and to increased costs from wastewater discharge fees (Tang et al. **II**).

More expensive: Tang et al. **II** concluded that decentralized softening (ion exchange and reverse osmosis) were 7-10 times more expensive than centralized softening (pellet softening, nanofiltration and CARIX®) in a specific case. These results indicate that centralized softening is more economically feasible than decentralized. Worst case, widespread decentralized softening could compromise the potential socioeconomic benefits from centralized softening.

Lack of control with water quality: Decentralized ion exchangers remove nearly all hardness. The final hardness is set by only softening a fraction of the incoming water, and mixing hard and softened water after the ion exchanger. Ion exchange increases the water Na^+ concentration (Tang et al. **I**). If the ratio between softened and hard water is set wrongly, the Na^+ concentration may exceed the Danish guideline of 175 mg/L (Miljø- og Fødevareministeriet, 2019a) or the water may become $CaCO_3$ dissolving if the hardness is too low, which can lead to corrosion (Tang et al. **II**).

Negative environmental impact: Despite assuming that households purchasing decentralized softening are more inclined to reduce their soap and detergent usage compared to households being centrally supplied by softened water, Beeftink et al. (2021) found a net increase in the annual carbon footprint per person if installing decentralized ion exchange. Thus, the environmental benefits that may be achieved by centralized softening (Godskesen et al., 2012), may instead result in an overall negative impact if decentralized softening becomes too widespread.

Chloride pollution: Ion exchangers regenerated with NaCl produce a highly concentrated waste stream (eluate) with elevated Cl^- concentrations. In some parts of the world, widespread use of decentralized ion exchange has resulted in environmental challenges, since Cl^- is not removed during conventional wastewater treatment and can increase the salinity of the recipient (Bakshi et al., 2021). In Denmark, treated wastewater is both discharged to the sea and fresh water recipients, the latter being most vulnerable towards increased salinity.

Thus, widespread implementation of decentralized softening in Denmark may result in increased consumer convenience by reducing negative effects from hard water, but may result in increased costs, negative environmental impact and water quality not meeting the drinking water guidelines. In Denmark, softening at the many small DWTPs supplying e.g. < 100 people resembles decentralized softening in e.g. an apartment building. Thus, in parts of Denmark, implementation of softening at the DWTPs will be in small scale with potentially higher costs, but still with better control of the drinking water quality (Tang et al. **II**). Larger drinking water utilities supplying fairly hard or harder water (Figure 6) should consider centralized softening to supply all consumers in their supply areas with softened water to avoid widespread use of decentralized softening.

4.4 Optimizing the implementation of softening in Denmark

4.4.1 Fulfilling treatment objectives

In Denmark, the implementation of softening is driven by a wish to increase consumer convenience, which leads to an overall treatment objective of reducing the negative effects from hard water experienced by the consumers (Section 2.1.2). Most of the effects from water hardness experienced by the consumers are from lime scaling that can be predicted by the CCPP (Section 3.2, Tang et al. **III**). Thus, the CCPP is an essential indicator to include to when evaluating softening scenarios in Denmark.

The Danish socioeconomic studies considered only water hardness, and not CCPP, when assessing the effects from softening (Cowi, 2011; Deloitte, 2015b, 2015a; Rambøll, 2017). Consequently, they assumed equal effects experienced by the consumers independent of the technology (pellet softening and strong-acid ion exchange). However, softening technologies affect the overall mineral composition of drinking water and thereby CCPP differently (Tang et al. **I** and **II**). At the same softening depth, pellet softening, which reduces the water alkalinity in addition to hardness, is expected to result in a lower CCPP compared to ion exchange that only removes hardness (Tang et al. **I**). This is yet to be taken into account when evaluating the effects from softening at a societal level.

The environmental and socioeconomic benefits from centrally softened water are closely related to the effects experienced by the consumers (Figure 9), since reduced use of soap and detergents, increased service life span of appliances etc. result in both environmental and economic benefits (Beeftink et al., 2021; Rambøll, 2017).

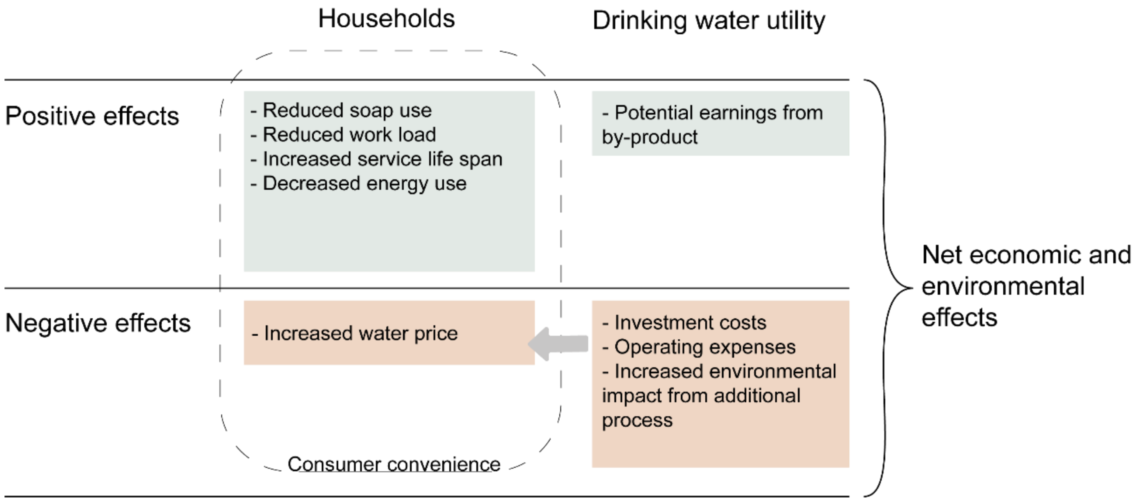

Figure 9: Centralized softening increases consumer convenience at household level, whereas net socioeconomic and environmental impacts also depend on the softening process at the DWTP.

Implementation of softening results in investment costs and increased operating expenses at the DWTP (Rambøll, 2017; van der Bruggen et al., 2009), which also has a negative environmental impact from construction materials, chemical and energy use etc. (Beeftink et al., 2021; Godskesen et al., 2012). In Denmark, the finances of water utilities are regulated by law and increased costs at the DWTP must be compensated by an increased water priced paid by the consumers (Miljøstyrelsen, 2021). Thus, implementation of softening results in an increased water price experienced as a negative effect by the consumers (Rambøll, 2017, Figure 9).

Minimizing lime scaling increases consumer convenience at household level. However, the overall environmental and socioeconomic effects from softening depend also on the softening process and its implementation at the DWTP (Figure 9). Thus, Danish water utilities implementing softening should design the softening process to minimize water hardness and CCPP, without the water becoming aggressive, at the lowest possible costs and environmental impact to meet the treatment objectives outlined in Section 4.2.

4.4.2 New pesticides findings and treatment requirements

Danish drinking water supply is relying on groundwater resources that are increasingly threated by pesticides and their metabolites (GEUS, 2021). From 2017 and onwards, an expanded analysis programme found a number of previously unmeasured pesticides and metabolites in Danish groundwater samples. Where the Danish groundwater monitoring program detected pesticides in 33 % of the monitoring wells in 2017, the number had increased to 58 % in 2019 due to findings of desphenylchloridazon, methyldesphenyl-chloridazon, 1,2,4-triazol and N,N-demethylsulfamide (GEUS, 2021).

Some of the Danish water utilities struggle to produce the required amount of water if abandoning groundwater contaminated with pesticides, e.g. by changing their abstraction patterns. Thus, in the future it may be necessary to remove pesticides at the DWTP. Together with softening this development has a paradigm shifting potential in Danish drinking water treatment from simple to advanced treatment. It also calls for flexibility in the process design of new DWTPs. Even though a DWTP does not currently treat groundwater contaminated by pesticides, new compounds can be detected in the coming years and the water treatment process must be adaptable to potential findings. Some softening technologies, nanofiltration and reverse osmosis, has the potential for removing pesticides together with water hardness (van der Bruggen et al., 2001), which may be favourable in some cases where pesticide concentrations can be reduced to below the guideline concentration while achieving the desired softening depth.

4.4.3 By-product reuse potentials

Lime/soda-ash softening and pellet softening remove hardness by precipitation forming a solid $CaCO_3$ by-product. In lime/soda-ash softening, it is removed as sludge, whereas it is removed as solid pellets in pellet softening. The sludge (or water treatment residues) from lime softening can be used for soil amendment and subsurface fill (Blaisi et al., 2015).

Pellet softening is already implemented in Denmark by HOFOR, Frederiksberg Forsyning and St. Heddinge DWTP with more installations planned (Section 4.1, Figure 7). Consequently, pellet reuse applications must be identified to avoid pellets being disposed as waste, which is associated with higher costs and is undesirable from a circular economy point of view. Reuse of pellets has a small environmental benefit in terms of reduced carbon footprint from substitution of e.g. limestone from quarries (Beeftink et al., 2021). Moreover, Beeftink et al. (2021) argued that pellets and lime sludge captures CO_2 during precipitation, increasing the environmental benefits. In the Netherlands, pellets are reused in concrete and as construction filler, but also as seeding material in pellet softening and in high sales value markets such as cosmetics and carpet production (AquaMinerals, 2019).

The reuse possibilities for pellets can be improved by the process design (Tang et al. **IV**). Crushed pellets or quarry limestone can be used as seeding material instead of sand to increase pellet purity (Schetters et al., 2015). In addition, different ions (e.g. iron and manganese) precipitate with $CaCO_3$ as impurities in pellets affecting pellet color (Figure 10), which can limit reuse applications (Tang et al. **IV**).

Figure 10: Pellets from pilot-scale softening at Regnemark DWTP (after rapid sand filtration), Dalum DWTP (after rapid sand filtration) and Lindved DWTP (after aeration) (Tang et al. IV).

Softening after rapid sand filtration in a traditional (Danish) groundwater treatment train of aeration and rapid sand filtration results in pellets with less impurities and more reuse possibilities (Tang et al. **IV**). On the other hand, inorganic contaminants such as nickel can potentially precipitate with pellets, which is beneficial from a human health perspective (Rosborg and Kozisek, 2019), but may limit reuse (Tang et al. **IV**). Considering pellet characteristics and reuse already during design of the softening process can improve reuse possibilities (Tang et al. **IV**).

4.4.4 Other aspects

Other aspects are relevant to include when implementing softening in Denmark, including:

Human health: Drinking water contains minerals that are essential to human life (WHO, 2017). Softening affects the overall mineral composition of the drinking water and thereby also essential minerals (Tang et al. **I**). Although Mg^{2+} is not regulated in Danish legislation (Miljø- og Fødevareministeriet, 2019a), Kozisek (2020) recommended a minimum Mg^{2+} concentration of 10 mg/L and 20-40 mg/L as an ideal range to achieve a protective effect against cardio-vascular diseases. In the period 1980-2017, the mean Mg^{2+} concentration on Zealand (with the highest Ca^{2+} and Mg^{2+} concentrations) was 18.2 mg/L (Wodschow et al., 2018), which is already below the ideal range prior to softening. Thus, Mg^{2+} removal is relevant to avoid when implementing softening from a precautionary principle. DMF-S is an indicator for dental caries and is negatively affected by drinking water softening due to Ca^{2+} removal (Tang et al. **I**), but also depends on the fluoride concentration (Arvin et al., 2017). On the other hand, improvements in the overall dental health in Denmark has reduced the DMF-S and affect the DMF-S more than drinking water quality (Rygaard and Albrechtsen, 2012). Thus, preventive measures may compensate an increase in DMF-S from softening.

Guideline concentrations: The produced water must comply with the Danish drinking water legislation (Miljø- og Fødevareministeriet, 2019a). Ion exchange, pellet softening with sodium hydroxide and soda-ash softening increase the Na^+ concentration (Tang et al. **I**). In 1980-2017, the Na^+ concentration varied from 9.1 mg/L (2.5 % percentile) to 130 mg/L (97.5 % percentile), but was highest in the Eastern part of Denmark with the hardest water (Wodschow et al., 2018). Thus, the Na^+ guideline of 175 mg/L may be exceeded with some softening technologies or the Na^+ concentration may limit the achievable softening depth (Tang et al. **I**), which must be considered when designing the softening process.

Corrosion: The Danish "Code of practice for domestic water supply systems" (DS 439) includes several corrosion indicators such as the Larson ratio, HCO_3^- and Cl^- to evaluate corrosion risks for cast iron, hot dip galvanized steel, copper and stainless steel (Dansk Standard, 2009). Due to the complexity in evaluating the effects on corrosion, several corrosion indicators should be included to avoid adverse corrosion effects (Tang et al. **I**). Corrosion from negative CCPP may also occur when mixing hard and soft water in the distribution networks (Imran et al., 2006), which should be considered if several DWTPs supply the same distribution networks, as in the case for the Copenhagen area supplied by HOFOR.

Existing facilities: Although it also indirectly affects the investment costs, the requirements for building area and height vary depending on the technology – both for the technology itself and its supporting facilities (Tang et al. **II**). If implementing softening in an existing DWTP, it may not be possible to expand the building in area or height, which may exclude softening technologies with a large building footprint. Moreover, the many small DWTPs may not have permanent staff employed. Some technologies require more maintenance (e.g. pellet softening) compared to others (e.g. ion exchange) (Tang et al. **II**).

Social acceptance: Traditionally, the drinking water treatment in Denmark has been characterized as simple water treatment without chemical addition. Especially the addition of chemicals to the water has been mentioned in the public debate on softening in Denmark (e.g. Blom, 2018; Novafos, 2021). A new softening technology, Plastic Air Softening (PAS), is currently being tested in Denmark (AA Water, 2021). It relies on CO_2

stripping, which increases pH and causes $CaCO_3$ to precipitate onto a plastic filter material and is removed from the reactor as $CaCO_3$ “flakes” (Aktor, 2018). The development of PAS shows that even though softening technologies are commercially available, specific circumstances in Denmark (i.e. a tradition for simple treatment without chemical addition) result in new criteria for the technologies and may consequently lead to development of new technologies.

Wastewater discharge: In Denmark, softening is legally classified as “advanced water treatment” and water utilities must apply for permission to soften the water from the local municipality (Miljø- og Fødevareministeriet, 2019b). The application must contain information on wastewater streams from the DWTP that are discharged to recipients and/or the sewer system. The wastewater quality and quantity from softening varies depending on the technology (Tang et al. **II**). Moreover, softening can also affect the wastewater from the other processes at the DWTP (Tang et al. **II**). Pellet softening on untreated groundwater removes the majority of iron and manganese from the water that is otherwise removed with backwashing of the rapid sand filters (Tang et al. **IV**), thereby changing the chemical composition of the backwash water (Tang et al. **II**). Saline wastewater from especially ion exchange and membrane separation can be barrier for achieving the necessary permission from the municipality and can hence limit the number of possible softening scenarios.

4.5 Selection of indicators for evaluating softening in Denmark

To optimize decision support when implementing softening in Denmark, I propose a framework where decision support encompassing technical, economic, environmental and social dimensions, is extended with an in-depth analysis of water quality related issues, thereby combining the two frameworks presented in Sections 3.1and 3.2 (Figure 11).

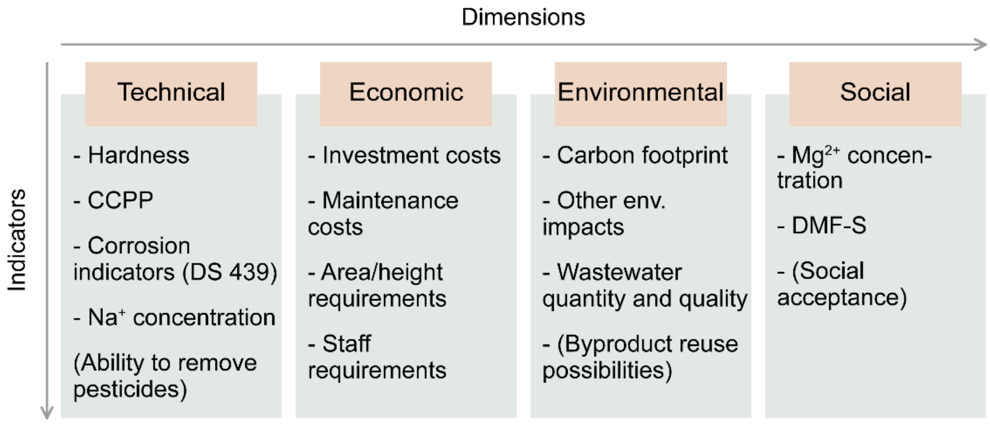

Figure 11. Indicators to be included when evaluating softening technologies in Denmark. Indicators in brackets will only be relevant in some cases.

The indicators include hardness and CCPP to evaluate the consumer convenience (Section 4.4.1). Other technical indicators include corrosion indicators from the Danish code of practice (DS 439) (Dansk Standard, 2009) and the Na^+ concentration that risk exceeding guideline limitations. If relevant, the ability to remove pesticides or other organic contaminants can be included in the evaluation, since it may be relevant to remove both hardness and contaminants in a single treatment process (van der Bruggen et al., 2001).

Economic indicators should at least include investment, operating and maintenance costs, but the building area and height requirements, wastewater quality and quantity as well as staff requirements and availability are relevant, and could limit the choice of technology (Figure 11).

Environmental indicators such as carbon footprint should be included to assess the environmental impact from the softening process (Figure 11). If pellet softening is considered, by-product reuse possibilities should be considered during the design of the softening process, since the process design affects the chemical composition of pellets and thereby their reuse possibilities (Tang et al. **IV**).

Finally, health effects from e.g. Mg^{2+} removal and DMF-S should be included. Tang et al. **I** concluded that all softening technologies remove Ca^{2+} and thereby have a potentially positive effect on the occurrence of atopic eczema. Consequently it is not included in this overview, but should be included as an effect from softening in any future socioeconomic studies evaluating the effects from softening.

Softening technologies will affect the suggested indicators differently depending on local conditions including source water quality, annual water production, existing facilities, local authorities etc. Due to this, softening in Denmark is not a “one size fits all” solution where a specific technology and softening depth will be the best solution at all DWTPs. Thus, it is necessary to carefully select indicators considering specific conditions and evaluate the indicators for each individual DWTP to optimize the implementation of softening. In the next chapter, I discuss how indicators can be selected and quantified in practice.

Summary

- The main driver for implementing softening in Denmark is to increase consumer convenience, which is best evaluated by water hardness and the CCPP. In addition, softening should provide environmental and socioeconomic benefits that are increasingly important for Danish water utilities.
- Centralized softening offers several benefits compared to decentralized softening including lower costs and water usage, better control of water quality and the possibility for supplying all consumers in a supply area with softened water.
- Pesticides not previously analyzed for are increasingly detected in Danish groundwater. Together with softening, this potentially causes a paradigm shift from simple treatment to advanced treatment. This calls for water treatment design that is flexible and can be adjusted for unexpected challenges, and also opens up for synergies where both pesticide and hardness removal are addressed.
- Evaluation of softening scenarios in Denmark should, in addition to hardness and CCPP, at least include corrosion indicators according to DS 439, Na^+ and Mg^{2+} concentrations, costs, area/height requirements, carbon footprint, wastewater quality and quantity, and DMF-S.
- Local conditions will determine which softening technology and process design is the best. Indicators should be adapted for and evaluated in each specific case.

5 Discussion

This discussion will focus on the practical applications of indicators in decision support when implementing softening, including: quantification of indicators, the process from selection of indicators to decision making, and the balance between increasing information requirements and need for practicability. Finally, the future for drinking water quality is discussed in light of designing the optimal water quality.

5.1 Selecting and quantifying indicators

With the treatment objective(s) and other relevant criteria as basis, indicators must be carefully selected for evaluation of softening scenarios. Hamouda and Huck (2010) used experts within the water sector to assess the suitability of different indicators for evaluating the sustainability of point-of-use and point-of-entry water treatment. The overall scope was to develop a complete DSS that can generally be applied (Hamouda et al., 2014). The case study of softening in Denmark demonstrated that in the case of softening, the selection of suitable indicators depends highly on local conditions (Section 4.5). Consequently, the selection of indicators can be based a generic array of indicators (e.g. Figure 11), but should always be considered in each individual case.

The indicators presented in this thesis require a broad field of expertise and methods to be quantified. The methods for quantifying the indicators in Figure 11 include water quality modelling (e.g. PHREEQC) for CCPP calculations (Tang et al. **III**), softening process modelling to estimate e.g. energy and chemical usage, estimates of investment and operation costs (Tang et al. **II**), and interviews for evaluating social acceptance (Godskesen et al., 2019). Such methods require multidisciplinary expertise and expert knowledge on e.g. unit costs, existing legislation and computerized models. Moreover, DWTP specific data such as source water quality as well as water production in different operating scenarios are required to evaluate softening. Thus, a drawback of increasing the number of indicators when evaluating softening is an increased need of expertise and additional work load required to quantify each indicator.

Even though many of the softening technologies have been used for decades, their effects on the overall mineral composition of drinking water are not fully understood (Tang et al. **I**). Furthermore, some water qualities may interfere with the softening process. For instance, Fe^{2+} concentrations exceeding 4 mg/L can interfere with $CaCO_3$ crystallization in pellet softening resulting in unwanted porous pellets (Ruhland and Jekel, 2004). Consequently, pilot-scale testing may be necessary to e.g. investigate the removal of specific ionic species or contaminants or to ensure that the softening process is not interfered by the source water quality.

5.2 From indicators to decision making

Selecting and quantifying indicators does not lead directly to decision making. To overcome the immense workload required for quantifying all indicators in all possible softening scenarios, the decision process can be sequential and start with an initial screening to exclude obviously unfeasible scenarios and limit the number of scenarios for further analysis (Hamouda et al., 2009).

In the case of Denmark, many drinking water utilities must decide whether to soften the drinking water centrally or not. Currently, centralized softening has mainly been implemented in the Eastern part of Denmark with the hardest water (> 3.6 mmol/L). However, Danish drinking water statistics revealed that 115 DWTPs annually deliver about 84 million m^3 fairly hard drinking water (2.1-3.2 mmol/L, 12-18 °dH) (Figure 6). Although both socioeconomic and environmental benefits are possible from softening at this hardness (Godskesen et al., 2012; Rambøll, 2017), it may not be technically and economically feasible at the individual DWTP level. At this stage, an initial screening at feasibility level could be sufficient to evaluate if *any* softening technologies are technically and economically feasible in the specific case. In the Netherlands, ten drinking water utilities are contributing with cost data in to a Standard Cost Calculator developed by Royal HaskoningDHV (Royal HaskoningDHV, 2018, Tang et al. **II**). The database contains about 2,600 projects and can be used for a quick cost estimate, however, associated with some degree of uncertainty (± 30 % for investments costs and ± 20 % for operation costs) (Royal HaskoningDHV, 2018). Similar tools would be beneficial in other countries for an initial screening of softening technologies and for selecting scenarios for further analysis.

Although multiple indicators are relevant to include in decision support, they may not be equally important. Different decision support tools are available for weighing indicators and evaluating scenarios such as MCDA (Hajkowicz and Collins, 2007). MCDA can evaluate and compare scenarios in case of multiple and conflicting objectives (Hajkowicz and Collins, 2007; Sadr et al., 2020), as in the case of softening.

5.3 Going into practice…

Although existing DSSs frameworks and decision support tools like MCDA provide consistent and transparent decision making, DSSs are seldom used exclusively. Specific circumstances such as a desire to use the same softening technology at all DWTPs operated by the same water utility can eventually have the highest weight and be decisive to the design of softening. Nonetheless, an evaluation of multiple indicators will still provide valuable information on both positive and adverse effects from softening that can e.g. facilitate future operation of the softening process or identify any preventive measures needed to compensate for adverse effects.

Increasing the number of indicators result in increased complexity and analysis requirements. Thus, the optimal decision support process must balance the information requirements and practicability (Figure 12).

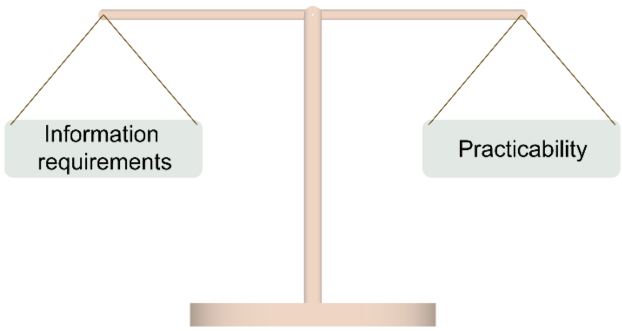

Figure 12: When implementing softening, decision support must balance information requirement and practicability.

Especially smaller drinking water utilities and DWTPs may have not the competencies for such evaluation and will need assistance from external experts. If decision complexity is too high, the utilities may decide not to even consider softening. In areas with hard water, the consumers not supplied centrally with softened water might purchase decentralized softening units, which can have adverse socioeconomic and environmental effects (Section 4.3).

To decrease the complexity it can be necessary to limit the number of indicators or make assumptions to simplify the evaluation. This can be by using calculation tools as presented in Section 5.2. The absolute environmental and socioeconomic benefits from implementing a specific softening technology are uncertain, since the correlation between hardness, CCPP and lime scaling in the actual drinking water systems are not fully understood (Tang et al. **III**). Comparing softening at a fixed softening depth or CCPP reduction by different technologies, and thereby assuming equal effects by the consumers, simplifies the evaluation to include only the processes at the DWTP, where costs and environmental impact can be reduced as much as possible to maximize the potential benefits from softening.

Finally, due to the uncertainty and research gaps still present when using indicators to evaluate the effects, an attempt to fully evaluate the technical, economic, environmental and social effects from different softening scenarios would only result in an approximation of the effects after implementing softening. Indicators are not ideal representations of the real world. Being aware of this uncertainty and the consequences from excluding or simplifying indicators from the evaluation is a key part of optimizing decision support when implementing softening.

5.4 Designing the ideal water quality

Reverse osmosis membranes remove nearly all minerals from the water together with contaminants such as pesticides (Bellona et al., 2004; Biesheuvel et al., 2020). Could removal of all minerals from the drinking water and subsequent remineralization, and thereby design of the final water quality, be the optimal solution for softening? In the case of Denmark and other parts of the world challenged by drinking water contaminants, it would provide the benefits from softer water and be a barrier against any future contaminants in the drinking water. Unfortunately, remineralization raises new challenges and questions, including “what is the ideal water quality” (Rygaard et al., 2011)? Although some water quality criteria have been suggested after remineralization (e.g. Lahav and Birnhack, 2007), they do not cover all minerals essential to human health (Rosborg and Kozisek, 2019).

This thesis has demonstrated that water quality is not only a technical issue but affects also human health, socioeconomy, environmental impact etc. Optimizing one aspect can result in suboptimal conditions in other aspects. Ultimately, drinking water quality must always meet legislative guidelines, but technologies like softening enables optimization and potential improvement of water quality. By carefully selecting and evaluating indicators, drinking water softening has the potential for benefitting the society and environment.

6 Conclusions

This thesis developed a framework for selecting indicators when evaluating softening scenarios that include the overall motivation for softening and local conditions with a novel focus on water quality, often neglected in existing DSSs. The thesis concludes that:

- Selecting softening technology and process design involves several technologies with many design options and deciding the softening depth (i.e. hardness removal), which complicates decision making.
- The motivation for implementing softening has shifted from “need to have” to comply with new Pb and Cu guidelines in drinking water to “nice to have” focusing on increasing consumer convenience and providing socioeconomic and environmental benefits. The main driver for softening should form the basis, together with local conditions, for selecting relevant indicators for evaluating softening scenarios to ensure that the technology is fit-for-purpose.
- With today’s increasing focus on sustainability, it is necessary evaluate softening in a broad systems perspective encompassing technical, economic, environmental and social dimensions. The broad systems view should be extended by a deeper analysis of effects from water quality changes on lime scaling, corrosion, human health etc. that has often been overlooked in literature.
- The case study of softening in Denmark illustrated that indicators can be selected to consider local conditions and challenges such as emerging pesticides, national standards for corrosion and potential legislative restrictions on wastewater discharge. Drinking water utilities must evaluate softening scenarios in each given case to consider e.g. the source water quality and local restrictions on building capacity and wastewater discharge.

The best softening technology in a given case meets the treatment objectives and legislative guidelines, while balancing the remaining indicators. Water quality in a broader sense should be included when evaluating softening to maximize the benefits from softer water and to identify possible adverse effects that may need preventive measures. Ultimately, drinking water softening can potentially increase consumer convenience while benefitting the society and environment.

7 Perspectives

The use of indicators, and particularly the increased use of water quality indicators, provides decision support when implementing softening. However, research gaps and challenges must still be overcome to realize the full potential and further develop the framework proposed in this thesis:

Refinement of indicators: Indicators are not perfect representations of reality, which is necessary to be aware of when applied in decision support. However, further research could lead to better accuracy in prediction. Especially, the CCPP is highly important to predict lime scaling by the consumers, but its correlation to the lime scaling in real drinking water systems is poorly understood.

Development of screening tools: In the Netherlands, water utilities have jointly contributed to a cost calculator for an initial screening of investment and operating costs of drinking water technologies. Similar tools in other countries could provide quick estimates to reduce the number of feasible softening scenarios for further analysis.

Technology development: Softening technologies are not static entities, but are constantly developed to e.g. reduce water usage or required chemical dosage. Simultaneously, new technologies are being developed that overcome some of the current challenges. New technologies that combine the mechanisms of existing softening technologies could potentially lead to more flexibility in controlling the final water quality and thereby compensate for some of the drawbacks of existing technologies.

This thesis focused on softening, but the concept of using water quality indicators as part of decision support can be applied whenever implementing technologies that alter the mineral composition of water. This could be other drinking water treatment processes, but also industrial processes involving water treatment.

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9 Papers

I **Tang, C.**, Rygaard, M., Rosshaug, P.S., Kristensen, J.B., Albrechtsen, H.-J. Evaluation and comparison of centralized drinking water softening technologies: Effects on water quality indicators. *Submitted.*

II **Tang, C.**, Merks, C.W.A.M., Albrechtsen, H.-J. (2019). Water softeners add comfort and consume water – comparison of selected centralised and decentralised softening technologies. *Water Supply* 19(7), 2088-2097.

III **Tang, C.**, Godskesen, B., Aktor, H., van Rijn, M., Kristensen, J.B., Rosshaug, P.S., Albrechtsen, H.-J., Rygaard, M. (2021). Procedure for calculating the calcium carbonate precipitation potential (CCPP) in drinking water supply: importance of temperature, ionic species and open/closed System. *Water* 13(42).

IV **Tang, C.**, Hedegaard, M.J., Lopato, L., Albrechtsen, H.-J. (2019). Softening of drinking water by the pellet reactor – Effects of influent water composition on calcium carbonate pellets. *Science of the Total Environment* 652, 538-548.

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The Department of Environmental Engineering (DTU Environment) conducts science based engineering research within three sections: Circularity & Environmental Impact, Climate & Monitoring and Water Technology & Processes. The department dates back to 1865, when Ludvig August Colding gave the first lecture on sanitary engineering.

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