



Water softeners add comfort and consume water – comparison of selected centralised and decentralised softening technologies

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ABSTRACT

Selected technologies for centralised or decentralised drinking water softening were evaluated based on technical, economic, environmental and aesthetic indicators to identify the optimal treatment technology for a given setting. To achieve this, we demonstrated that a number of important indicators beyond hardness reduction and costs have to be included. All the evaluated centralised softening technologies could reduce water hardness to the target of 1.3 mmol/L at the Dutch drinking water treatment plant Beilen. CARIX[®] treatment and pellet softening with Ca(OH)₂ resulted in a lower CCPP₉₀ (0.25–0.30 mmol/L) than nanofiltration (0.30–0.35 mmol/L). Decentralised reverse osmosis had a water consumption of >100%, whereas decentralised cation exchange had a water consumption of 2.5–4.5% which was comparable to centralised pellet softening (3.6%). Except for the electronic water conditioner that does not remove water hardness, the decentralised technologies were 7–10 times more expensive than the centralised technologies per m³ of softened water. The centralised softening technologies furthermore ensured supply of softened water to all customers in a water supply zone. Thus, in areas with hard water and limescale problems, investment in centralised softening at the local water utility is more optimal than widespread implementation of decentralised systems.

Key words | CCPP, decision making, drinking water treatment, hard and soft drinking water, water treatment residuals, water use

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INTRODUCTION

Hard drinking water increases the formation of limescale (mainly calcium carbonate (CaCO₃)) in household appliances and installations, which e.g. increases the use of descaling agents and reduces the service life of e.g. kettles and water heaters (Brink *et al.* 2004). Hard drinking water can also result in increased soap consumption (WHO 2011). Limescale formed on the inside of water pipes may reduce the flow capacity and may eventually even block it entirely. Furthermore, hard water can increase the solubility of lead and copper from distribution pipes and appliances, which may result in increased concentration in

the drinking water (Hofman *et al.* 2007). Hard water is caused by the presence of multivalent cations, mainly calcium (Ca²⁺) and magnesium (Mg²⁺) (van der Bruggen *et al.* 2009).

Centralised drinking water softening was implemented in the Netherlands in the 1980s to reduce the release of lead into drinking water (van den Hoven *et al.* 1998), but nowadays the driving force for implementing centralised softening has shifted towards a consumer comfort perspective by reducing limescale (Hofman *et al.* 2007). Water utilities can add softening to existing or new drinking

water treatment plants (DWTPs), thereby centrally providing softened drinking water to their customers. When centralised softening treatment is not provided, households and businesses sometimes install their own decentralised water softeners as point-of-entry or point-of-use water treatment devices.

Several softening technologies are available and they vary in terms of hardness and limescale reduction, but also in terms of e.g. water consumption, maintenance requirements, residuals, capital cost and operating expenditures, environmental impact and effect on corrosion. Despite the widespread implementation of both centralised and decentralised drinking water softening (e.g. Hofman *et al.* 2007; van der Bruggen *et al.* 2009), the overall performance of centralised versus decentralised softening technologies has not been evaluated.

The aim of this study was to evaluate selected technologies for centralised or decentralised drinking water softening using an array of relevant indicators including technical, economic, environmental and aesthetic criteria. A secondary aim was to evaluate the overall performance of centralised versus decentralised drinking water softening technologies.

METHODS

Selection of indicators

The selection of indicators for evaluating softening technologies was inspired by a framework developed to evaluate point-of-use and point-of-entry water treatment technologies (Hamouda *et al.* 2010). We adapted these criteria by including technical, economic, environmental and aesthetic indicators. Indicators for comparing softening technologies should reflect the motivation for drinking water softening, and in this case the driving forces were limescale and soap-use reduction.

- **Hardness reduction:** The softening technologies included in this study all reduce water hardness (i.e. removal of calcium and possibly also magnesium) except the physical water conditioner. However, the mechanisms for hardness removal vary, and for some

water types it may not be possible to meet the target hardness after softening.

- **Limescale reduction,** expressed by the Calcium Carbonate Precipitation Potential at 90 °C (CCPP₉₀): The CCPP quantifies the amount of CaCO₃ that can dissolve or precipitate from the water and provides a better estimate for limescale than e.g. the Langelier saturation index (Brink *et al.* 2004).
- **Water consumption:** Drinking water softening is typically associated with a water use. The amount of water used depends on the softening technology and its mechanism for hardness removal.
- **The quantity and quality of residuals:** Some softening technologies, e.g. pellet softening, produce both wastewater and solid residuals (van Dijk & Wilms 1991). The solid residuals can represent either a resource, if they can be reused, or waste if reuse applications are unavailable.
- **Operating and maintenance requirements:** Operating and maintenance vary depending on the softening technology, as well as the size and capacity of the DWTP, thereby affecting operating expenditures differently. For decentralised softening, operation is done by members of the household and maintenance is typically done by professionals (van der Bruggen *et al.* 2009; BWT 2019c).
- **Cost per m³ softened drinking water:** Both capital cost and operating expenditures were included when evaluating the different technologies.

Evaluation of centralised softening technologies

Three technologies were selected to represent centralised drinking water softening with different mechanisms for hardness removal: pellet softening with Ca(OH)₂, anaerobic nanofiltration and CARIX[®] treatment. Each technology was evaluated with respect to the indicators based on literature, the authors' personal experience with implementing water softening, and personal communications with technology suppliers (Veolia 2018).

The technologies were evaluated using the Dutch DWTP Beilen as case study, which is operated by the water utility Drenthe (WMD). DWTP Beilen has a total annual water abstraction permit of 4 million m³ groundwater, with a

design capacity of 650 m³/h. The groundwater has a hardness of 2.0 mmol/L (1 mmol/L = 100 mg CaCO₃/L) and the target water hardness selected by the water utility was 1.3 mmol/L. The groundwater also contains e.g. methane, iron, manganese and ammonia that must be removed to meet drinking water guidelines and that may interfere with softening (Supplementary Material A, available with the online version of this paper).

The cost estimates for each of the three potential water treatment schemes were at the level of a feasibility study with an accuracy of ±30% for capital cost and ±20% for operating expenditures. The cost estimates for pellet softening with Ca(OH)₂ and for membrane separation technologies were developed by the water utility Drenthe (Wessels & Galama-Tirtamarina 2018) with the Standard Cost Calculator Drinking Water (Royal HaskoningDHV 2019), and the assumptions and unit prices listed in Supplementary Material B (available online). The cost estimate for anaerobic nanofiltration was based on these cost estimates. Veolia developed the cost estimate for CARIX[®] for DWTP Beilen in December 2018 (Veolia 2018) and supplies the CARIX[®] technology.

Evaluation of decentralised softening technologies

Reverse osmosis, 'traditional' cation exchange with different mechanisms for removing water hardness and one physical water conditioner were selected to represent decentralised drinking water softening. Generally, scientific literature about decentralised softening technologies is limited. We contacted various suppliers of decentralised softening devices, however, none responded within the timeframe of this study. Consequently, the evaluation of decentralised technologies was made based on publicly accessible data by various suppliers and limited scientific references.

The cost estimates for cation exchange were based on an example calculation by the technology supplier BWT in Denmark for the AQA basic unit and were affected by the initial water hardness only (BWT 2019c). The calculations were based on drinking water with an initial water hardness of 2.0 mmol/L and operating expenditures were calculated for a household of three people with the average Danish daily water use of 107 litres per person (BWT 2019c). This example calculation was also used for the cost estimates for the other decentralised softening technologies. The

cost estimates included the purchase price and operational expenditures e.g. regeneration salt or filter replacement, excluded installation and water consumption, and were expressed as costs per m³ softened drinking water produced.

SOFTENING TECHNOLOGIES

Different softening technologies have different mechanisms for hardness removal (Table 1). Some softening technologies, e.g. lime-soda ash softening, pellet softening and CARIX[®], are complex and require special facilities and are therefore applicable only to centralised systems where all treatment can be accomplished at a central location. Other technologies, e.g. ion exchange, distillation and membrane separation, are applicable both to centralised and decentralised systems (Table 1).

Softening technologies for centralised softening

Pellet softening

Dosing a base changes the carbonic acid equilibrium, resulting in spontaneous crystallisation of CaCO₃. In pellet softening, the base is dosed in a fluidized bed reactor with seeding grains. CaCO₃ crystallises on the surface of the seeding grains, forming pellets. Calcium hydroxide (Ca(OH)₂) or sodium hydroxide (NaOH) is typically used as the base chemical (van Dijk & Wilms 1991).

In pellet softening, almost only Ca²⁺ is removed from the water due to the pH conditions inside the reactor. Thus, hardness caused by Mg²⁺ remains in the water, which limits the achievable softening depth (i.e. hardness reduction). CCPP reduction depends on the choice of base chemical. Ca(OH)₂ removes 2 moles HCO₃⁻ for each mole Ca²⁺ removed, which decreases CCPP more compared with NaOH where 1 mole HCO₃⁻ is removed from the water for each mole Ca²⁺ removed (van Dijk & Wilms 1991).

CaCO₃ pellets are the main residual from pellet softening and may be reused in industry. The water use for pellet softening is primarily associated with sand washing and pellet withdrawal and is typically 1%. Pellet softening requires post-treatment by filtration, which may also result in an increase of wastewater and sludge from backwashing of the filters.

Table 1 | Technologies for centralised and decentralised drinking water softening

Hardness removal mechanism	Technology	Centralised softening	Decentralised softening
Crystallisation/precipitation	Pellet softening ^a	x	
	Lime-soda ash softening ^{a,b}	x	
Ion exchange	Strong acid cation exchange ^{b,c}	x	x
	CARIX ^{®a}	x	
Pressure-driven membrane separation	Nanofiltration ^{a,b}	x	
	Reverse osmosis ^{a,b}	x	x
Electric-driven membrane separation	Electrodialysis ^b	x	
Temperature-driven distillation	Temperature-driven distillation	x	x
Chemical scale control	Chelation ^b		x
	Sequestration ^b	x	
Physical water conditioning devices ^d	Electronic and electrostatic devices ^{c,e}		x
	Electrolytic devices ^c		x
	Permanent magnets and electromagnets ^{c,e}		x

^aMons *et al.* (2007).^bAWWA (2016).^cBWT (2019a, 2019b).^dPhysical water conditioning devices do not soften the water by lowering water hardness, but claim to reduce limescale formation (Georgiou *et al.* 2018).^eGeorgiou *et al.* (2018).

Pellet softening also requires storage facilities for the chemicals (the base and CO₂ for pH adjustment after softening), seeding grains and the produced pellets, which require maintenance. The pellet reactor itself requires maintenance every 1–2 years, predominantly for removal of limescale. The storage facilities contribute substantially to the capital cost where economy of scale affects the contribution of these facilities to the overall investment of pellet softening. In general, the larger the plants' capacity the lower the cost per m³ of softened water.

CARIX[®]

Carbon Dioxide Regenerated Ion Exchange (CARIX[®]) can be designed for two operating modes: partial desalination or softening only (Höll & Hagen 2002). In the partial desalination process the ion exchange resin is a mixed bed of a weak-acid cation resin in the free acid form (H⁺) and a strong-base anion resin in the hydrogen carbonate form (HCO₃⁻). Ca²⁺ and Mg²⁺ in the feedwater are exchanged with H⁺ ions and SO₄²⁻, NO₃⁻ and Cl⁻ are exchanged with HCO₃⁻. CO₂ is formed as a result of the ion exchange and is removed from the water by air stripping or degassing.

This reduces the HCO₃⁻ concentration of the water thereby reducing the CCPP. In softening mode, the exchange resin consists of the weak-acid cation resin in the free acid form only (Höll & Hagen 2002).

Once the resin is saturated, it is regenerated with pressurised CO₂ dissolved in water, and wastewater (eluate) with the exchanged ions must be disposed, typically to a recipient. The water use for CARIX[®] treatment varies depending on the softening depth, since higher hardness removal requires a higher regeneration frequency, resulting in increased water consumption. Veolia reports a water usage ranging from 3.5% to 10% of the feedwater flow (Veolia 2018). No solid residuals are formed during CARIX[®].

A CARIX[®] plant requires steel vessels for e.g. the production of regeneration water, degassing and CO₂ recovery from the wastewater as well as various rotating equipment (e.g. pumps and blowers) consequently requiring some maintenance and substantially contributing to the capital cost. The total cost of CARIX[®] treatment is predominantly affected by the relatively high capital cost (Veolia 2018). Currently, CARIX[®] is implemented at DWTPs with a capacity ranging from 20 to 600 m³/h, thus predominantly at medium-sized water systems.

Nanofiltration

Nanofiltration is a pressure-driven membrane filtration process with pore sizes from 0.7 to 5–8 nanometres (Hoslett *et al.* 2018). Nanofiltration membranes reject both scale-forming Ca^{2+} and Mg^{2+} ions as well as SO_4^{2-} , while a fraction of e.g. Na^+ , HCO_3^- and Cl^- passes the membranes (van der Bruggen & Vandecasteele 2003). Nanofiltration typically requires antiscalant for scaling control and possibly some hydrochloric acid to lower the pH of the feedwater. The hardness reduction depends on the membrane type, but nanofiltration can result in nearly complete hardness removal (both Ca^{2+} and Mg^{2+}). The target hardness is achieved by blending non-softened bypass water with softened permeate water. The mixing does also allow for setting the desired CCPP.

The amount of wastewater (concentrate) from nanofiltration depends on the membrane system design, antiscalant and acid chemical dosages and the feed pressure. The amount of concentrate can range from 15% to 30% of the feedwater to a nanofiltration unit (van der Bruggen & Vandecasteele 2003). The wastewater has a high mineral content as well as the antiscalant chemical. No solid residuals are produced during nanofiltration.

Periodic replacement of membranes is needed, and the frequency depends on feedwater quality, feedwater treatment, membrane system design and operation. Pre-treatment of feedwater is usually required to decrease membrane fouling. Alternatively, membrane separation technologies can be implemented on anaerobic groundwater which reduces the risk of membrane fouling and the maintenance requirements. The time necessary for operation and maintenance of a membrane softening plant is relatively limited due to the high degree of process automation. The operating expenditures are predominantly related to the energy requirements of the high-pressure feed pump and to the chemical costs.

Nanofiltration softening plants are designed and constructed as modular plants. Thus, the overall investments and thereby the cost per m^3 are affected by the size and capacity of the DWTP, and by the required amount of water that must pass the nanofiltration membrane.

Softening technologies for decentralised softening

The following softening technologies do not require special facilities and are therefore also applicable for decentralised water systems. Cation exchange and reverse osmosis were included in this study, based on drinking water as feed water.

Cation exchange

The units for the cation exchange softening technology are typically equipped with a strong-acid resin that replaces Na^+ adsorbed to it with Ca^{2+} and Mg^{2+} present in the drinking water. Once the resin is saturated, regeneration takes place with sodium chloride (salt), and wastewater (eluate) with the Ca^{2+} , Mg^{2+} and Cl^- ions must be disposed (AWWA 2016).

Water leaving the cation exchanger has close to zero hardness and must be blended with non-softened bypass drinking water to achieve the desired hardness (BWT 2019a). Cation exchange softening does not alter the pH or alkalinity of the water. Consequently, the CCPP reduction is lower than for the other included softening technologies, unless close to zero hardness water is considered. The water use for regeneration can be as low as between 2.5% and 4.5%, depending on water softener size and model (BWT 2019a).

Reverse osmosis

Reverse osmosis uses the most dense membranes and can remove essentially all organic and inorganic constituents but is not an impermeable barrier to ionic species. Even though >95% rejection can be attained, complete rejection of target pollutants is hard to achieve (Bellona *et al.* 2004). Due to the high rejection, reverse osmosis produces water that has nearly zero hardness. Decentralised reverse osmosis is predominantly installed as point-of-use systems without the possibility to blend with non-softened water (Express Water 2019).

Reverse osmosis membranes in decentralised systems are typically a part of a so-called 'five stage drinking water solution' (Express Water 2019) with the stages: mechanical filtration, activated carbon adsorption, ultrafiltration,

reverse osmosis and activated carbon adsorption. The systems operate on incoming household water pressure and without antiscalant and/or acid chemical dosages, resulting in a high amount of concentrate to be discharged to the sewer system. According to the supplier, the typical discharge is 1 to 3 litres for every litre produced, which is affected by the water pressure, incoming water quality and water temperature (Express Water 2019). The systems are maintained by replacing the different filters and the reverse osmosis membrane. The frequency of replacement depends on e.g. the incoming water hardness (Express Water 2019).

Physical water conditioners

Physical water conditioners are not designed for water softening (i.e. removal of Ca^{2+} and Mg^{2+} from water) but to alter the characteristics of the hardness minerals within the water to prevent limescale formation (Georgiou et al. 2018). The mechanisms of electronic, electrostatic and magnetic water conditioners have been hypothesised (e.g. Coey 2012), but are not fully understood. Although several studies have been carried out on physical water conditioners showing a reduction in limescale formation (e.g. Georgiou et al. 2018), the effects may vary depending on the water quality

(Coey 2012) and no studies demonstrate effects in terms of e.g. reduction in soap and descaling agent use comparable to the other softening technologies included in this study.

The electronic water conditioning device by Hydropath Technology Ltd was included in this study, which applies an electrical field to the pipe and the water contained within. According to Hydropath, the technology works by emitting a varying electrical field into the water, causing the CaCO_3 particles to form in suspension, which are then washed away with the flow. The electronic water conditioners produce no wastewater or residuals (Hydropath 2019).

EVALUATION OF SOFTENING TECHNOLOGIES

Water treatment schemes for centralised softening

Different treatment schemes were required at DWTP Beilen in order to achieve the target hardness of 1.3 mmol/L depending on the softening technology (Figure 1). Aeration and rapid sand filtration or dual media filtration were necessary for removal of methane, iron, ammonia and manganese upstream of pellet softening or CARIX[®]. CARIX[®] was designed to operate in softening mode with a

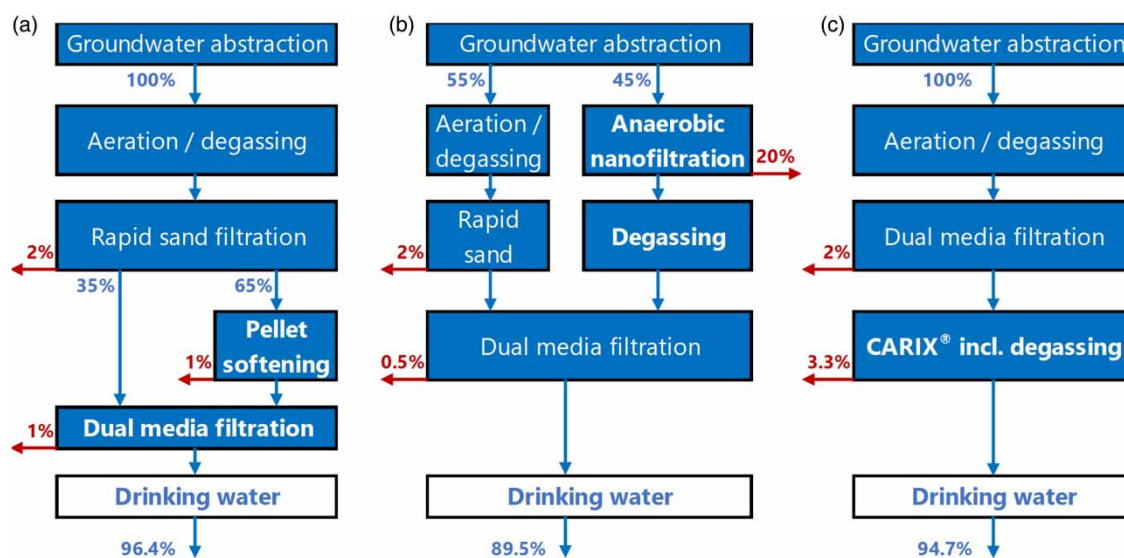


Figure 1 | Potential water treatment schemes for Dutch DWTP Beilen with (a) split stream pellet softening, (b) split stream anaerobic nanofiltration and (c) full stream CARIX[®] treatment. Blue (vertical) arrows represent drinking water flow and brown (horizontal) arrows represent wastewater flow. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/ws.2019.088>.

weak-acid cation resin in the free acid form only and was followed by degassing (Veolia 2018). Pellet softening was applied to 65% of the filtered water and was followed by dual media filtration (Wessels & Galama-Tirtamarina 2018). Nanofiltration was applied directly to 45% of anaerobic groundwater (so-called split stream), followed by degassing and rapid sand filtration (Figure 1).

Softening technologies for centralised water systems

Despite the different technologies and treatment schemes, the costs per m³ of softened water were comparable for all three softening technologies: 0.15–0.20 USD per m³ (Table 2; Supplementary Material C, available with the online version of this paper). Pellet softening requires 8–12 hours per week for maintenance, which is more than nanofiltration (4–8 hours per week) and CARIX[®] (2–4 hours per week). The target drinking water hardness of 1.3 mmol/L was met by all three softening technologies (Table 2). The CCPP₉₀ after pellet softening with Ca(OH)₂ and after CARIX[®] treatment were comparable (0.25–0.30 mmol/L) and slightly better than by anaerobic nanofiltration (0.30–0.35 mmol/L). The water treatment scheme with anaerobic nanofiltration had the highest total water use (10.5%) compared with pellet softening (3.6%) and CARIX[®] (5.3%). The wastewater from nanofiltration is highly concentrated

and contains antiscalant, whereas the wastewater from CARIX[®] typically can be discharged to a recipient due to its lower concentration of minerals. Pellet softening produces a solid residual, pellets, as the only included technology.

The results from DWTP Beilen represent a specific geographic case with a specific groundwater composition. Technologies should be evaluated for each specific case prior to choosing softening technology. Nonetheless, the case study provides an indication of the performance within each indicator.

Technologies for decentralised water systems

The cost of softened water treated by decentralised technologies varied from USD 0.3 per m³ for the electronic water conditioner to USD 2.2 per m³ for the cation exchange device (Supplementary Material D, available online). The costs related to the water consumption were not included and hence the operating expenditures for the reverse osmosis installation will be higher due to the water use that exceeds 100%.

Both cation exchange and reverse osmosis can remove nearly all water hardness (Table 3), whereas the electronic water conditioning device does not remove hardness. The highest reduction of CCPP₉₀ is expected with reverse

Table 2 | Comparison of three different softening technologies for centralised water softening treatment at DWTP Beilen with a design capacity of 650 m³/h

Indicator	CARIX [®]	Nanofiltration	Pellet softening
Hardness reduction	From 2 to 1.3 mmol/L	From 2 to 1.3 mmol/L	From 2 to 1.3 mmol/L
CCPP ₉₀	0.25–0.30 mmol/L	0.30–0.35 mmol/L	0.25–0.30 mmol/L
Water use (total)	5.3%	10.5%	3.6%
Water treatment residuals quantity	60 tonnes of dry solids per year (iron sludge)	33 tonnes of dry solids per year (iron sludge)	60 tonnes of dry solids per year (iron sludge); 80 tonnes of dry solids per year (lime sludge)
Softening treatment residuals quantity	132,000 m ³ of eluate per year	360,000 m ³ of concentrate per year	290 tonnes of pellets per year
Softening treatment residuals quality	High mineral content eluate	High mineral content concentrate with antiscalant	Yellow-white coloured pellets (reusable)
Operating requirements softening technology	2–4 hours per week	4–8 hours per week	8–12 hours per week
Cost per m ³ for groundwater treatment	USD 0.35–0.45 per m ³	USD 0.35–0.45 per m ³	USD 0.35–0.45 per m ³
Cost per m ³ for softening treatment	USD 0.15–0.17 per m ³	USD 0.16–0.18 per m ³	USD 0.18–0.20 per m ³

Table 3 | Comparison of three selected softening technologies for decentralised water softening or conditioning treatment

Indicator	Cation exchange ('traditional')	Reverse osmosis	Electronic water conditioning device
Hardness reduction	Total removal possible	Total removal possible	None ^a
Level of documentation	Well documented	Well documented	Limited documentation
CCPP ₉₀ reduction	Low to high	High	None ^a
Water use (total)	2.5–4.5% ^b	>100% ^c	No water use
Softening treatment residuals quantity	No solid residuals	No solid residuals	No residuals
Softening treatment residuals quality	High mineral content eluate	High mineral content concentrate	No residuals
Maintenance requirements	Low	Low	Low
Cost per m ³ for softening treatment/conditioning	USD 2.2 per m ³	USD 1.4 per m ³ plus the cost of water discharged	USD 0.3 per m ³

^aHardness and CCPP₉₀ are not affected, since physical water conditioning devices do not soften the water by lowering the calcium and magnesium content and do not radically alter the water chemistry.

^bBWT (2019a, 2019c).

^cExpress Water (2019).

osmosis compared with cation exchange, since HCO₃⁻ is removed in addition to water hardness. The electronic water conditioning device may have an effect on limescale formation, but since the water composition does not change, CCPP₉₀ is not expected to change (Table 3).

The water consumption varies substantially for the decentralised water systems, from the electronic water conditioning device with no water use, to a reverse osmosis system where the water usage in most cases will exceed 100% of the feedwater to the unit (Table 3).

The decentralised water systems vary more in performance compared with the centralised water systems. The reverse osmosis system has the highest water usage, but also reduces CCPP₉₀ the most. An electronic water conditioning device has the advantage that it has neither water use nor production of residuals. On the other hand, the effects on limescale reduction are uncertain.

Centralised versus decentralised drinking water softening

For water utilities, high water consumption of a specific technology can limit the amount of drinking water produced if e.g. groundwater abstraction permits are at risk of being exceeded. Furthermore, discharging wastewater to e.g. the sewer is associated with increased operating expenditures

unless direct discharge to a recipient is possible. For households, discharging water will increase the water use and thereby increase costs. However, they are not challenged by the restrictions of e.g. abstraction permits that utilities experience and water consumption is hence less critical for households.

When a water utility decides not to invest in centralised softening treatment in areas with hard water, many households in these areas may instead implement decentralised softening. Large water consumption due to widespread decentralised softening treatment with a variety of softening technologies can also affect the water utility by an increased overall water demand, beyond the control of the water utility.

Except for the electronic water conditioner, the decentralised technologies were 7–10 times more expensive than the centralised technologies per m³ of softened water, indicating that large-scale operation results in lower costs. Thus, it may be beneficial for water utilities to consider implementing centralised softening to supply all customers with the benefits of softened water and thus avoid widespread implementation of decentralised technologies. When choosing the optimal treatment technology for either centralised or decentralised softening, a number of important indicators beyond hardness reduction and costs have to be included. Both the total water consumption of a water treatment scheme including a specific softening

technology and the options for wastewater discharge and residuals must be included in the evaluation.

CONCLUSION

We evaluated selected technologies for centralised and decentralised drinking water softening. None of the included technologies performed best within all six indicators. Consequently, including only hardness removal and costs when choosing a softening technology may result in a less optimal choice compared with an evaluation also considering e.g. the CCPP₉₀, solid residuals and wastewater production. For the selected case study, the following was concluded:

- The centralised softening technologies (CARIX[®], pellet softening with Ca(OH)₂ and nanofiltration) performed equally well in terms of hardness removal at DWTP Beilen. Pellet softening with Ca(OH)₂ and CARIX[®] treatment resulted in the lowest CCPP₉₀. The decentralised softening technologies (cation exchange and reverse osmosis) were able to remove nearly all water hardness, and the lowest CCPP₉₀ was expected with reverse osmosis.
- Decentralised reverse osmosis had the highest water use (>100%) followed by: centralised anaerobic nanofiltration (10.5%), centralised CARIX[®] (5.3%), decentralised 'traditional' cation exchange (2.5–4.5%), centralised pellet softening (3.6%) and the decentralised electronic water conditioning device (no water use).
- The centralised softening technologies generally performed better than the decentralised technologies (cation exchange and reverse osmosis) in terms of costs (7–10 times cheaper than the decentralised technologies).

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