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Water quality – Environmental benefits – Costs**

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Twenty years of experience with central softening in The Netherlands: Water quality – Environmental benefits – Costs

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Abstract

Central softening has been utilized by the Dutch water utilities since the late 1970s. It was introduced in the water treatment process as a method to supply water with an optimum water composition to prevent lead and copper release and to prevent excessive scaling. Twenty years of experience show that central softening is beneficial for public health, has significant environmental benefits and that it lowers social costs. Also enhanced consumer comfort is a result of distribution of water with low scaling potential. This paper will describe the water quality improvements and will quantify the benefits realized in practice.

Introduction

Central softening has been applied successfully in The Netherlands since the late 1970s. A long discussion and an intensive research effort to develop the softening technology preceded the break through at full scale (Graveland *et al.*, 1983, Van Ammers *et al.*, 1986). Since then, the installed softening capacity increased very rapidly (see Figure 1). Nowadays, almost all drinking water in The Netherlands is conditioned to an optimal water quality to prevent corrosion and excessive calcium carbonate scaling. In approximately 50 % of the production capacity, softening is required to meet realize the required water quality.

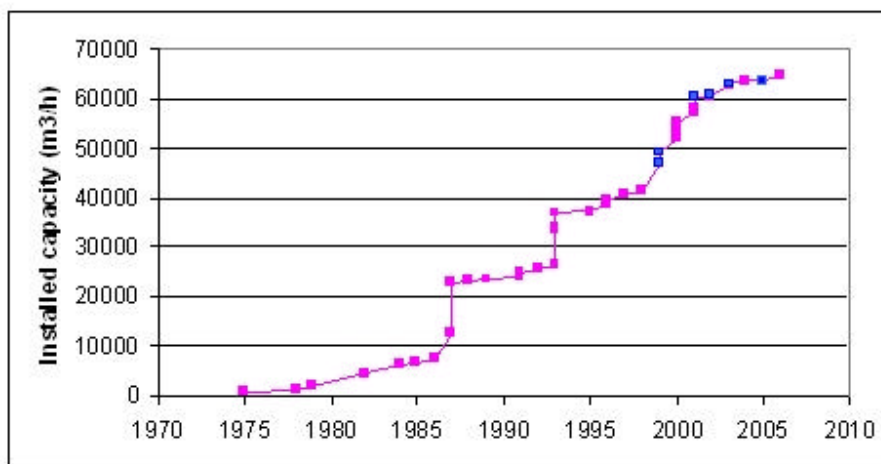


Figure 1. Development of cumulative softening capacity in the Netherlands (Blue dots are nanofiltration plants) (Mons *et al.*, 2006).

Figure 2 shows the distribution area's of the Dutch water utilities in 2005. The last decade this map has changed a lot due to company mergers. The number of water utilities has decreased significantly over the last years. It is expected that more companies will merge in the near future.



Figure 2. Distribution area's of the Dutch Water Supply Companies (situation 2005).

Waternet

Waternet (formerly Amsterdam Water Supply) produces drinking water for the City of Amsterdam and its surrounding municipalities. The total installed capacity is 101 million m³ (annual production approximately 90 million m³). The main raw water sources – both surface water – are the river Rhine and seepage water from the Bethune Polder. They are treated at two production plants: Leiduin (70 million m³/y) and Weesperkarsel (31 million m³/y). Central softening is applied at both plants since 1987.

Vitens

Vitens is the largest water supply company in the Netherlands, serving more than 4 million customers in the

provinces Friesland, Gelderland and Overijssel with drinking water. A total capacity of 260 million m³/year is produced from groundwater sources at 85 water treatment plants. Softening is applied at 24 treatment plants: 13 use fluidized bed pellet softeners (76 million m³/y total production) and at 10 locations nanofiltration is applied. The total production capacity involving membrane filtration therefore is 23 million m³/y. Nanofiltration is selected when hardness is to be removed in combination with color, sulphate or organic micro pollutants. For one water treatment plant, reverse osmosis is used to get a full barrier for hardness, sulphate and organic micro pollutants. The total production capacity of softened water is 100 million m³/y, which is 38 % of the total annual drinking water production of Vitens. At some locations where naturally very soft water is treated, marble filtration is used to reach the optimum water composition.

Brabant Water

Brabant Water is located in the southern part of the Netherlands and produces 180 million m³ drinking water annually. Also 10 million m³/year industrial water is produced. The main source for industrial water is the river Meuse. At the moment 34 production locations are operated for the drinking water production, using groundwater as a source. At 4 locations central softening is applied (35 million m³/y) using fluidized bed softeners. The newest plant is opened in 2005 in Nuland (9 million m³/y). At 4 more locations, central softening plants are under construction

Table 1: Softening target values for drinking water.

Parameter ¹	Waternet	Vitens	Brabant Water
Total Hardness (mmol/l)	1.5	1.0 < TH < 1.5	< 1.43
TACC90 (mmol/l)	< 0.1	< 0.6	
PACC (mmol/l)			< 0.4
TIC (mmol/l)		> 1.5	
pH	8.3 - 8.4	7.8 < pH < 8.3	7.8 < pH < 8.3
Saturation Index	+0.35 < SI < +0.45	-0.2 < SI < +0.3	0 < SI < +0.3
Corrosion Index			< 1

¹ TACC90: Theoretical calcium carbonate scaling potential at 90°C; PACC: Practical calcium carbonate scaling potential; TIC: Total inorganic carbon.

(25 million m³/year) with a total investment of 20 million Euros. At 6 locations (35 million m³/y), naturally very soft ground water is treated with marble filtration, or milk of lime is added, to reach the optimum water composition.

Reasons for softening

Public health

Research in 1970s and 1980s has resulted in recommendations for the optimum composition of drinking water that aim at minimization of lead and copper release from the supply system and house installations, prevention of corrosion of asbestos cement and metal pipe materials and prevention of scaling (Van den Hoven and Van Eekeren, 1988). The recommendations strongly depend on inorganic water quality parameters such as acidity (pH) and total inorganic carbon (TIC) (all concentrations in mmol/l):

$$\max\left(0.38 * TIC + 1.5[SO_4^{2-}] + 5.3\right) < pH < 8.3 \quad (1)$$

$$TIC > 2 \quad (2)$$

$$-0.2 < SI < 0.3 \quad (3)$$

$$CI = \frac{[Cl^-] + 2[SO_4^{2-}]}{TIC} < 1 \quad (4)$$

Here *SI* is the Langelier Saturation Index and *CI* is the corrosion index.

As lead and copper (and other heavy metals, e.g. nickel) are important factors for public health, softening plays a very important role in reducing these compounds in drinking water.

A second aspect on public health is found in the fact that many consumers will install tap water softening devices. The effects of these point-of-use (POU) devices are that risks for public health increase. Poor maintenance will lead to poor microbiological water quality, especially when no persistent disinfectant is used during distribution (as in The Netherlands). Furthermore, the use of POU devices may result in increased corrosivity of the water, leading to higher metal concentrations. Finally, the lack of adequate water quality monitoring when POU devices are used, is a threat to public health.

Environmental benefits

The environmental benefits of central softening are realized in several aspects. The first important aspect is the reduction of calcium carbonate scale formation in water heating equipment. Absence of scale is required to have an optimum heat transfer in these devices. So prevention of scale formation by using softened water will prevent additional energy use and e.g. CO₂ emission.

The second aspect is the environmental burden by chemicals. Roughly three categories can be distinguished: 1) copper and other corrosion products, 2) compounds related to washing powder (detergents, phosphate(replacements)), 3) salt emission by POU ion exchange devices.

Finally, the environment benefits from central softening because of the pellets waste stream can be controlled and reused in agriculture and steel production (Van Dijk and Wilms, 1991).

Social costs

The use of central softening will increase drinking water costs directly. On the other hand, consumers will have reduced costs for maintenance of warm water equipment and can use less amounts of washing powder. If these costs are taken into account, the additional drinking water

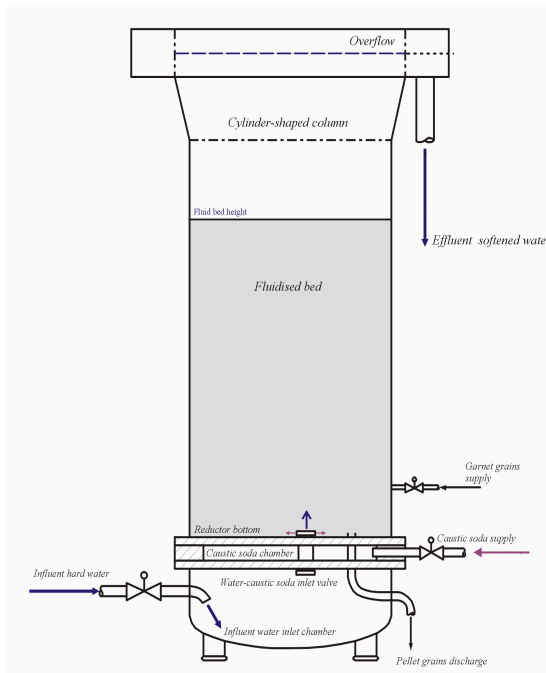


Figure 3. Schematic view of a flat bottom fluidized bed pellet softening reactor.

costs will outweigh the household costs. Furthermore, many people would install POU devices, which are expensive to buy and use. In general it is believed that the costs for society will be significantly less if central softening is used.

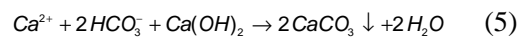
Esthetics and comfort

The fourth reason for softening is consumer convenience and comfort. By softening, staining and hard laundry can be prevented. Also, the water gets a better taste and no film formation on a glass of tea will occur.

Softening technology

Pellet softening

Softening in The Netherlands is mainly done in pellet softeners. Softening is initiated by addition of a base according to the following chemical reactions (Graveland *et al.*, 1983):



When lime is used for softening the bicarbonate content of the water is also reduced. For each mole of calcium, 2 moles bicarbonate will be removed. For sodium hydroxide softening, only one mole of bicarbonate is removed per mole of calcium and one mole of sodium is added to the water.

Calcium carbonate will crystallize at the surface of sand grains present in a fluidized bed. The sand grains will grow until a size of approximately 1 mm is reached. Pellets are abstracted from the fluidized bed periodically and new sand grains are added.



Figure 4. Two examples of pelletreactors. Left: Leiduin water treatment plant (Waternet); Right: Treatment plant Nuland (Brabant Water)



Figure 5. The Rodenmors nanofiltration plant (Vitens).

Several design variations of the reactor exist. These variations are mainly found in the bottom construction (flat bottom, conical bottom), the reactor feed construction (nozzles, tangential) and the base dosing equipment (nozzles, lances, dosing star). Figure 3 shows a schematic view of a flat bottom Amsterdam type reactor. Figure 4 shows examples of a flat bottom and a conical bottom reactor.

Although much experience is present nowadays to design reactors, the process is still studied fundamentally. Aspects as fluid bed management and process automation are important issues in this area (Rietveld *et al.*, 2005)

Nanofiltration as a softening technique

Nanofiltration is a membrane filtration technique that is especially suitable for hardness removal, because it removes calcium and magnesium almost completely. Also sulphate and organic matter (color) are removed effectively. When a complete removal of organic micro pollutants is desired, reverse osmosis is preferred because of the higher rejections.

Vitens applies nanofiltration on raw anaerobic groundwater (Nederlof *et al.*, 2001; Nederlof *et al.*, 2003). The low hardness permeate is aerated and mixed with untreated raw water; the blending ratio is determined by the required hardness values. A post treatment with rapid sand filtration to remove iron and ammonia follows. Finally, the pH is corrected to obtain the optimal water composition.

The recovery of the nanofiltration is 80-90 %, using anti-scalants to prevent scaling of sparingly soluble salts. This means that 10-20 % of the feed stream has to be discharged as membrane concentrate to a local surface water.

Twenty years of central softening: results and experience

Water Quality

Softening is an important improvement for water quality. After softening total hardness of the water will be reduced to a value between 1 and 2.5 mmol/l. Depending on the softening base used, either the sodium concentration increases (NaOH) and/or the hydrogen carbonate content will be lowered ($\text{Ca}(\text{OH})_2$).

Table 2 gives an overview to the hardness related water quality parameters. The data from Waternet (Leiduin) show that water is softened at a target value of 1.5 mmol/l. For Brabant Water the target hardness is somewhat lower: 1.4 mmol/l. For Vitens the target hardness is 1.0 mmol/l. In practice however, the hardness of the finished drinking water varies between 1.0 and 1.5

Table 2: Water quality parameters of raw and treated drinking water.

Technology	Parameter	Unit	Waternet (Leiduin) Pellet softener, NaOH		Vitens (Rodenmors) Nanofiltration		Brabant Water (Nuland) Pellet softener, Ca(OH) ₂	
			Raw ³	Treat'd ³	Raw	Treat'd	Raw	Treat'd
	Ca	mg/l	76.8	43.1	100	53	94	56
	Mg	mg/l	9.7	9.5	6.3	3.5	5.9	6.1
	TH	mmol/l	2.3	1.49	2.8	1.5	2.5	1.6
	Na	mg/l	46.6	76.4	34	21	99	77
	Cl	mg/l	87.2	93.5	9	11	153	108
	HCO ₃ ⁻	mg/l	197.0	157.2	341	200	308	299
	SO ₄ ²⁻	mg/l	52.5	52.1	10	5	21	13
	pH		7.89	8.35	7.0	7.9	7.3	7.8
	TACC ₉₀	mmol/l		0.32	0.95	0.5		0.97 ⁴
	SI		0.37	0.48	-0.2	+0.26		0.58
	CI ¹		1.1	1.4	0.06	0.13		0.65
	Cu solub exp ²				-	1.2		
	Cu solub ³	mg/l	2.21	1.21	4.6	1.3		1.8
	Pb solub ³	µg/l	166	102	298	168		182

¹ Corrosion index (see equation 4)

² Calculated plateau value (see equations 7 and 8)

³ Five year average

⁴ TACC at 10 °C

mmol/l. As expected, the pellet softening process reduces the calcium carbonate content in the water, leaves the magnesium concentration unchanged and increases the sodium concentration (in the case sodium hydroxide is used as base). Furthermore, the scaling potential of the water is reduced by approximately 20 %.

Copper and lead

One of the main reasons for introduction of central softening were the environmental and health effects of copper and lead release. Research by Van den Hoven and Van Eekeren (1988) resulted in two equations that predict the copper and lead solubility in stagnant water (16 hour plateau value):

$$Cu_{Max}(mg/l) = 0.52 \cdot TIC(mmol/l) - 1.37 \cdot pH + 2 \cdot [SO_4^{2-}](mmol/l) + 10.2 \quad (7)$$

$$Pb_{Max}(mg/l) = -141 \cdot pH + 12 \cdot T(^{\circ}C) + 1135 \quad (8)$$

For a long time, copper solubility was determined in a standardized copper test tube set up, with a standard of 3 mg/l (plateau value). This standard was replaced in revision of the Dutch Drinking Water Decree by 2 mg/l in a random day time sample, corresponding to the EU drinking water directive (EC, 1998). This standard is considered to be less stringent than the old one.

The introduction of pellet softening in Nuland in 2005 (Brabant Water) showed that the copper emission reduced from 2.3 mg/l Cu to 1.8 mg/l Cu. This resulted in a reduction of 30 % of the total copper emission to the environment. At a production rate of 9 million m³/y this is 4.5 tons. At the water treatment plant Rodenmors (Vitens), almost a factor 3 reduction of copper solubility was observed after introduction of nanofiltration (see Figure 6).

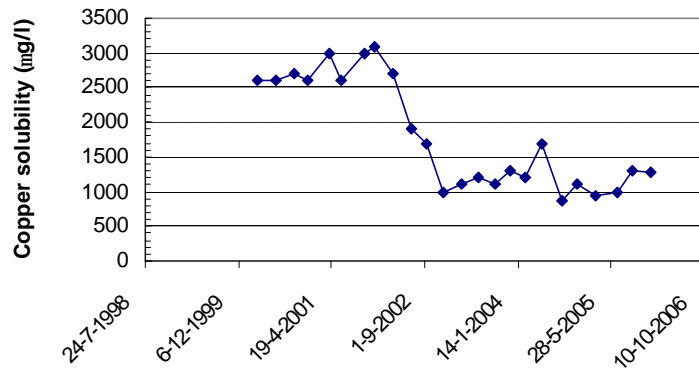


Figure 6. Copper solubility before and after the introduction of nanofiltration at the Rodenmors (Vitens) water treatment plant at the beginning of 2002.

As a result of the reduction of the copper and lead solubility, the concentration of these metals at the consumers tap is very low. Figure 7 shows the cumulative frequency distribution of copper and lead concentrations found in water samples in the distribution system in Amsterdam. The copper concentrations are always below the standard of 2 mg/l at the tap. For lead 90% of the observations is below 10 µg/l. This means that most of the time water fulfills the lead standard. On the other hand, in 10 % of the cases, the lead standard could not be complied with. In general it is seen that conditioning is not sufficient to comply with the lead standard. Therefore, lead pipe materials in the distribution system have been banned. The occasional high lead values found (up to 200 µg/l!), can to be awarded to the presence of old lead pipes in house installations, outside of the responsibility of the water supply company.

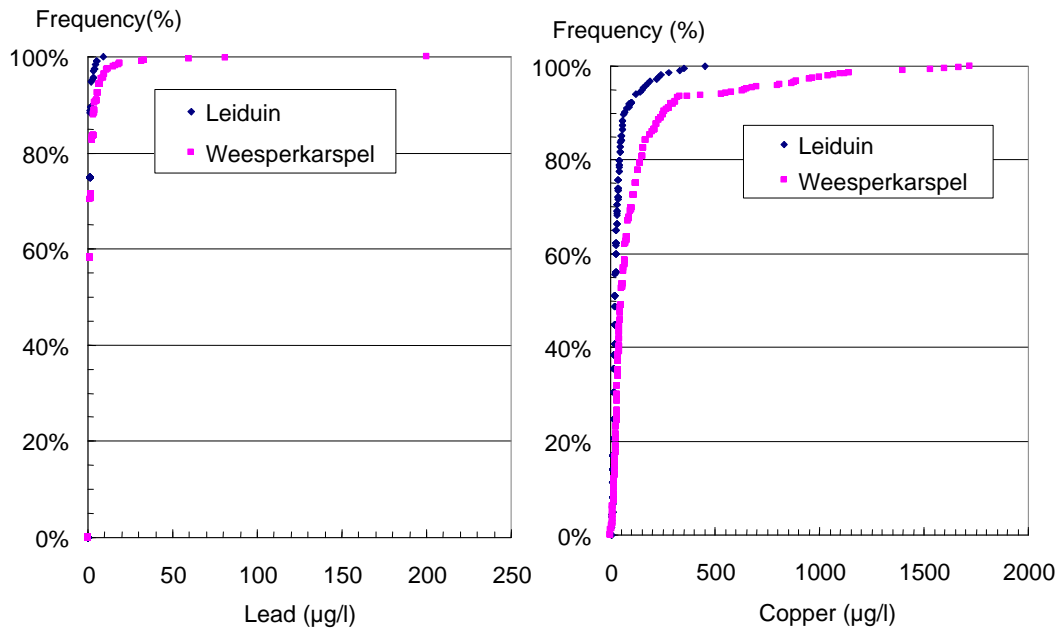


Figure 7. Frequency distributions of copper and lead concentrations found in the Amsterdam distribution area.

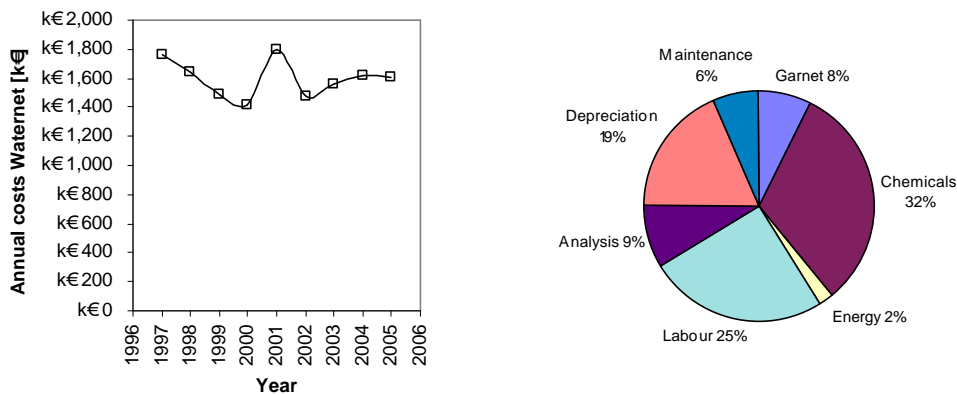


Figure 8. Total annual operation and maintenance cost and cost breakdown for softening at Waternet. Total installed capacity approximately 101 million m³/y, average production 90 million m³/y.

Costs

Central softening at large scale is relatively inexpensive. Figure 8 shows the annual costs for treatment of 101 million m³/year (installed capacity). On average the costs were €1.6 mln per year or approximately €0.02 per m³. The variations are mainly caused by variations in sodium hydroxide market price.

When central softening is applied at smaller scale, like the majority groundwater treatments in The Netherlands, the process will become more expensive. Operation and maintenance cost can increase to approximately €0.25 per m³. An average family (annual use 100 m³) will therefore pay approximately €2 to €25 extra for their drinking water, due to the introduction of softening. In ground water treatment this typically contributes for 35 to 55 % to the total production costs of drinking water.

On the other hand, application of central softening leads to financial benefits. These benefits can be divided in direct savings at consumer level and social cost benefits. The direct cost reductions, because of lower maintenance on warm water equipment, less washing powder use, reduced staining of sanitary fittings, less energy demand and taste are estimated at approximately €20 per year. Furthermore, costs for POU equipment, estimated at € 83 per year, can be added for comparison reasons, as is shown by a societal cost benefit study conducted by Brabant Water (Ruijgrok *et al.*, 2005; Van Nieuwenhuijze *et al.*, 2005). Similar savings are reported by Merkel (1998). In Germany, more POU equipment is used. He concludes that annual savings can be realized between €23 and € 190 per family of 4 persons. If POU investments are taken into account, savings can increase up to €300.

Social or indirect cost savings can be realized by reduced sewerage treatment costs and reduction costs related to environmental issues (e.g. copper emission, sludge volume). These costs are difficult to quantify, but are generally believed to be significant.

Environmental benefits

The environmental benefits of softening are found in the reduction of copper emission, reduction of the environment with detergents and phosphates, and lower energy consumption in warm water equipment. It is difficult however to quantify and compare these effects. Application of Life

Cycle Analysis (LCA) gives a good and objective evaluation of the environmental benefits of softening (Lindfors *et al.*, 1995; EC, 1992; Jensen *et al.*, 1997).

The methodology was applied to the softening system of Waternet by Regueira (2000). Environmental impact by the softening process itself included evaluation and quantification of NaOH, energy and garnet consumption, indicated by the blue production line in Figure 9. Below a total hardness of 1 mmol/l the environmental impact was estimated. It was assumed that the impact would deviate from linearity because chemical demand will probably increase at higher hardness removal levels.

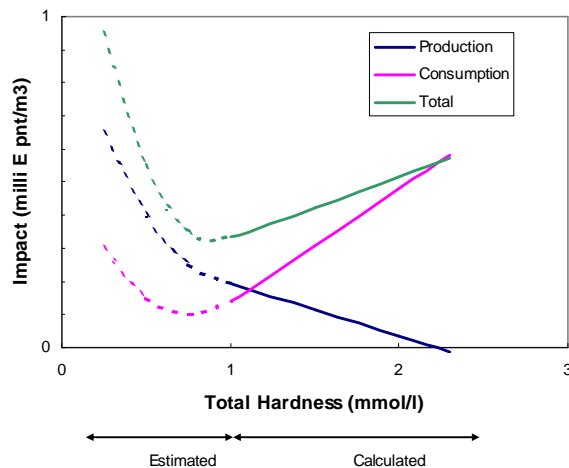


Figure 9. Optimization of the environmental impact by application of central softening (values indicative) (Regueira, 2000).

The effect of softening for the consumer was calculated by the effect on lead and copper release, the washing powder consumption and energy consumption for warm water. The three items were weighted for the amount of water consumed. The results are marked in Figure 9 by the pink line, whereas the green line represents the total environmental impact of softening. At higher hardness levels, the consumption will decrease if the hardness decreases, because the metal solubility and the energy and chemical consumption will decrease. Below a certain value however the consumption line will increase again because the water at very low hardness levels is aggressive and only very high pH values bring the water in equilibrium. Within the standardized pH limits the water remains aggressive at low pH and copper and lead release will increase again.

From the results it is concluded that there is a clear optimum level of total hardness. The exact position of this optimum level will depend on local situations and on the assumptions made in the LCA approach, clearly is below 2.5 mmol/l of total hardness.

Concluding remarks

Twenty years of experience with central softening and conditioning of drinking water in the Netherlands have well demonstrated the benefits for public health, the environment, costs and therefore society in general. Also, consumers benefit from having softened water at their tap. It reduces their overall costs and improves their comfort and leads to a more sustainable society.

The Dutch water utilities all strive to supply water with optimal conditioning. In approximately 50 % of the production capacity, softening is required to meet the guidelines for the optimal composition. This level is almost completely reached.

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