# Investigation of sustainable methods to reduce water hardness in drinking water treatment plants

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# Abstract

Water hardness is caused by magnesium and calcium ions ($Mg^{2+}$ and $Ca^{2+}$), and can result in formation of deposits, destruction of soap and increase of copper corrosion in old plumbing pipes. To soften the originally hard groundwater supplying 20% of Malmö's drinking water, Bulltofta water treatment plant imports burned lime from Germany. Approximately 66 mg/L calcium is removed in the treatment plant, lowering hardness levels from around 17 °dH to 6 °dH.

Previous experiments using plant biomass, pumice stone or plastic have demonstrated capacities for removal of $Mg^{2+}$ and $Ca^{2+}$ in water. As such, they were considered as sustainable options for reducing water hardness at Bulltofta. Theoretical calculations on the amounts required for each alternative, and their potential economical cost were made, and their environmental impact was investigated. All calculations are purely theoretical and should be experimentally validated, before definite conclusion can be drawn.

Plant biomass showed most promise as an alternative, and further investigations on plant biomass common in Sweden could yield positive results. Rapeseed is such an example, as it has a similar composition to sugarcane bagasse, which has been proven to adsorb $Mg^{2+}$ and $Ca^{2+}$. Currently, the investigated alternatives are not economical nor environmentally friendly. Additionally, daily quantities required of each alternative makes them infeasible for Bulltofta.

**Keywords:** Water hardness, sustainability, Bulltofta water treatment plant, water hardness reduction, plant biomass, plastic, pumice stone, adsorption

# Populärventskaplig sammanfattning

**Undersökning av hållbara alternativ för vattenavhärdning på Bulltofta vattenverk**

Vatten som innehar stora mängder magnesium och kalciumjoner ($Mg^{2+}$ och $Ca^{2+}$) kallas för hårt vatten och klassifierasoftast via den så kallade tyska graden: °dH. Uppskattningsvis innehåller 1°dH 7.1 mg/L Ca och 4.3 mg/L Mg. Hårt vatten kan bilda avlagringar, bryta ner tvål och bidra till kopparkorrosion i rörsystem. Ökade koncentrationer koppar i vattenrör kan i sin tur leda till negativa hälsoeffekter, och vid akuta överdoser leda till koma eller död inom några timmar.

Bulltofta vattenverk pumpar upp grundvatten med en hårdhet på 17°dH, som avhärdas ner till 6 °dH innan det förser 20 % av Malmös dricksvattensbehov. I nuläget importerar Bultofta bränt kalk från Tyskland, för att minska hårdheten i en avhärdningsprocess, som innebär en minskning på omkring 66 mg Ca per liter vatten.

Målet med rapporten är att undersöka hållbara alternativ för att minska vattnets hårdhet på Bulltofta, både på en ekonomiskt och miljövänlig plan, vilket görs via teoretiska beräkningar anpassade till de värden som återfinns på Bulltofta. Viktigt att ha med sig är att beräkningarna bör testas och godkännas experimentellt, och den teoretiska naturen av rapporten inte tillåter dragningen av slutgiltiga svar gällande alternativen som undersöks.

Tidigare experiment har visat att växtbiomassa, pimpsten och engångsplast, har kapaciteten att adsorbera $Mg^{2+}$ och $Ca^{2+}$ från vattenlösningar. Resultaten i rapporten tyder på att alldeles för stora mängder växtbiomassa, pimpsten eller plast skulle behövas för att avhärda de omkring 3 465 000 $m^3$ vatten som passerar Bulltofta varje år. Plast skulle exempelvis kräva mellan 44 eller 49 ton , pimpsten omkring 50 ton och växtbiomassa mellan 11 och 13 ton per dag. Som ytterliga käppar i hjulen finns lagar kring avfallsproduktion och miljöfarlig verksamhet från den svenska miljöbalken, det nya europa direktivet (EU) 2019/904 för engångsplast, samt de stora utsläpp av $CO_2$ som skulle tillkomma vid transport. De ekonomiska och miljömässiga kostnaderna är för tillfället alldeles för stora för att alternativen ska kunna tillämpas på Bullotfta.

Dock har tidigare forskning kring växtbiomassa för avhärdning av vatten visat positiva resultat och bör undersökas vidare. De experiment på biomassa som undersökts i rapporten baseras alla på icke-svenska växtalternativ (sockerröstblast, aktivt kol gjort på kokonötsskal eller kaffeskal), och man bör titta närmare på svenska växter, så som *Brassica Napus*, den raps som odlas i Skåne. Växten innehar liknelser med sockerrörsblast, och kan potentiellt binda $Mg^{2+}$ och $Ca^{2+}$. Fortsatt forskning kring detta alternativ bör därför fokusera på möjligheterna kring användning av svensk biomassa, så som raps.

# Contents

# Abbreviations

Ca: Calcium
$Ca^{2+}$: Calcium ion
Mg: Magnesium
$Mg^{2+}$: Magnesium ion
CaO: Calcium oxide
SEK: Swedish crowns
AC: Adsorption Capacity
Cu: Copper
$CaCO_3$: Calcium carbonate
CSAC: Coconut shell activated carbon
CNSAC: Cashew nut shell activated carbon
EMMB: Sugarcane bagasse grafted with EDTAD
EDTAD: Ethylenediaminetetraacetic dianhydride

# Chapter 1

# Introduction

In the 1900's, Malmö's population grew drastically. Providing an increasingly larger population with clean and potable water required a heightened use of water treatment plants, and in 1948, Vomb water treatment plant was put in operation joining Bulltofta water treatment plant. Around this time, large concentrations of iron sludge started to be noticed in the city's wiring. Adding to the problem were corrosion issues in galvanised iron pipes from house property, made worse from the hard water pumped up by the water treatment plants *(Areskoug, 2020)*.

The continuous contribution of hard water to corrosion in water pipes has made Bulltofta water treatment plant, or Bulltofta for short, interested in investigating sustainable alternatives for water softening. The report aims to investigate such possible alternatives, which could lead to the optimising and increasing of efficiency for water softening at Bulltofta. A prospective use of new sustainable alternatives for water softening could further lead to a reduced use of chemicals, decreased $CO_2$ release and increase time between material maintenance of the water treatment plant *(Areskoug, 2020)*.

## 1.1 Hypothesis

There are more sustainable solutions to decrease water hardness, than what is currently used at Bulltofta water treatment plant.

## 1.2 Questions and issues

The report aims to answer several questions circling back to the hypothesis, providing answers to these questions in a satisfactory manner. The aspiration is to provide clarifications on the use of potential sustainable alternatives for water softening at Bulltofta. Questions are as follow:

1. What previous research could be considered as sustainable alternatives for water softening?
2. What would be theoretical amounts required for such alternatives to soften the water at Bulltofta water treatment plant?
3. What are theoretical costs of such alternatives, and are they cheaper than the current alternative used at Bulltofta water treatment plant?
4. What environmental effects and laws should to be taken into account?
5. Could the alternatives in the report be used today for water softening at Bulltofta water treatment plant?

# Chapter 2

# Background

## 2.1 Water

For life to exist on earth, water is an essential factor. It is so important, that the United Nations has made clean water and sanitation one of the 17 sustainable development goals for 2030 *(United Nations, 2020)*. Around 17% of the world's population is unable to obtain clean and safe water from protected or nearby sources, and 51% of the population obtains water from some sort of centralised (piped) system. For those 51%, it is important that water quality remains high during distribution *(Sengupta, 2013)*. One problem the water industry has been struggling with for a long time, is Copper (Cu) corrosion in water pipes, which tends to be worsened by hard water *(Dietrich et al., 2004)*.

### 2.1.1 Hard water

Hard water is defined as water with high concentrations of calcium and magnesium ions ($Ca^{2+}$ and $Mg^{2+}$). Usually, distinction is made between carbonated hardness and non-carbonated hardness. When metals combine with some form of alkalinity, they form carbonated hardness, which can be removed by boiling the water. Non-carbonated hardness is more complicated to remove, and as such, is sometimes called permanent water hardness *(Sengupta, 2013)*. As only non-carbonated hardness is mentioned in this report, it is henceforth referred to as hardness, for simplicity's sake.

Groundwater tends to have higher levels of water hardness, due to the percolation of water through Ca and/or Mg minerals found in the ground. This water rich in Ca and Mg is not known to have any negative health effects. On the contrary, it has the potential to supply people with important supplements *(Sengupta, 2013)*. Ca concentrations up to (and exceeding) 100 mg/L are regularly found in natural water sources, especially groundwater. Mg on the other hand, is usually found at lower concentrations, rarely above 100 mg/L in groundwater *(WHO, 2010)*.

Groundwater tends to have a pH range between 6 and 8.5, similarly to surface water *(Oram, 2020)*. Extreme pH values can cause eye, skin and mucous irritation. Further negative effects, such as hair fibre swelling and gastrointestinal irritation in sensitive individuals, can be seen at pH between 10 and 12.5 *(Fawell et al., 2004)*.

Water hardness can be measured in several different units. A common unit is the "German degree" (°dH), calculated as the sum of Ca in water *(Livsmedelsverket (a), 2020)*. As a rule of thumb, 1 °dH is roughly composed of 7.1 mg/L Ca and 4.3 mg/L Mg *(NODAVA, 2020)*, or 10 mg/L CaO *(Livsmedelsverket (a), 2020)*. Apart from the German degree, mg/L calcium carbonate ($CaCO_3$) is also commonly used, referring to the amount of $CaCO_3$ in the water *(US Geological Survey,2020)*. The classifications of hard water in °dH and mg/L $CaCO_3$ can be found in *table 2.1*, having been compiled from *(Sengupta, 2013 and NODAVA, 2020)*.

Table 2.1: Different classification levels of water hardness in German degree *(°dH)* and concentration $CaCO_3$ *(mg/L)*, *(Sengupta, 2020 and NODAVA 2020)*

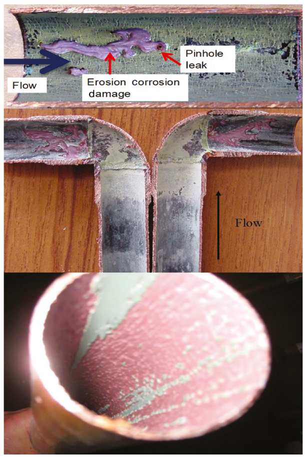
| **Water** | **German degree (°dH)** | **Concentration $CaCO_3$ (mg/L)** |
|---|---|---|
| Very soft | 0-2 | 0-60 |
| Soft | 2-5 | 0-60 |
| Medium hard | 5-10 | 61-120 |
| Hard | 10-20 | 121-180 |
| Very hard | >20 | >180 |

$Mg^{2+}$ and $Ca^{2+}$ are responsible for two damaging effects undesirable to the customer using hard water. These effects are the formation of deposits and the destruction of soap. Deposits of ions responsible for water hardness occurs due to reaction with soap anions, dulling clothes and reducing soap efficiency *(Park et al., 2007)*.

Contact with hard water can result in expensive breakdowns in boilers, cooling towers and plumbing. Furthermore, heating hard water causes carbonates to precipitate out of the solution, forming scales in pipes and surfaces. These scales result in plugged pipes and restricted flow. In boilers, this leads to ineffective heat transfer and loss of energy *(Puretec, 2020)*. Despite these effects, concerns with water hardness tends to be more connected to its contribution of Cu corrosion in water pipes, as this could generate high concentrations of Cu in potable water, resulting in health risks *(WHO, 2010)*.

### 2.1.2 Copper

Cu is a metal naturally found in the environment. An essential element for plants and living creatures, it is found in rocks, soil, water and air. Used for a variety of different products, Cu is commonly found in older plumbing pipes *(ATSDR, 2011)*. If ingested in too large doses, it can have negative health effects, such as gastrointestinal distress due to gastric or small bowel erosion. Acute overdoses of Cu can cause early appearance of cardiovascular collapse, coma and death within hours *(LiverTox, 2017)*.




*Cu corrosion damage in water pipes (Roy et al., 2014).*

Studies from Europe, Canada and USA have found Cu levels in drinking water to be anywhere between ≤0.005 to >30 mg/L, mainly due to corrosion inside Cu plumbings *(WHO, 2010)*. With Cu and Cu alloy pipes used widely in residential plumbing *(Dartmann, 2010)*, high concentrations of Cu in drinking water can quickly become a problem.

Cu release in water is no only affected by hard water, but also by pH, alkalinity and temperature. Low pH and high temperature increase its release in water *(Boulay and Edwars, 2001*. According to Dartmann et al. *(2010)*, a higher pH results in a decrease of Cu solubility, implying further protection from Cu corrosion in pipe installations from residential areas. Sepehr et al.*(2013)* points to fluctuations in hydrogen ions ($H^+$) in different pH environments, affecting binding sites for $Mg^{2+}$ and $Ca^{2+}$. A lower pH will find $H^+$ competing with $Mg^{2+}$ and $Ca^{2+}$, in order to bind onto the surface of the adsorbents.

Temperature has been known to affect Cu corrosion in water pipes. As pipes are usually buried in soil, outside temperatures can affect water temperature inside the pipes. As a result, the severity of Cu corrosion may differ depending on the season *(McNeill and Edwards, 2002)*, and presumably, geographic location.

### 2.1.3 Limit values

Europe has a collective limit for Cu in drinking water set to 2 mg/L. The Swedish national limit for Cu in water has been set to the much lower concentration of 0.2 mg/L *(Livsmedelsverket (b), 2020)*. There is no real limit for water hardness, although softer water is preferred *(VASYD (a))*.

## 2.2 Sustainability and Swedish environmental goals

The word sustainable encompasses many different definitions and branches, such as cleaner production, pollution control and eco-design. Often, the term sustainable depends on context, with differences in term usage, geographical locations and vague definitions *(Glavič and Lukman, 2007).*

In Sweden, chapter 1 §1 of the Swedish Environmental Code (sw: Miljöbalken), states that the Environmental Code was created to promote sustainable development, so that current and future generations will have a healthy and good environment. As such, any development should be built on the understanding that nature has a value worth protecting, and that a person's right to change and use nature is joined with a responsibility to administer it well *(SFS 1998:808).*

To help with this task, Sweden has a number of national environmental goals composed of 16 environmental quality objectives, as well as several milestones within the environmental and sustainability objectives. This project can be linked to two of the Swedish environmental goals:

- **Non-toxic environment:** toxic substances in the environment made or extracted by society, should not hurt people's health nor the biological diversity.
- **Well built environments:** cities, urban areas or other built on areas should be developed into good and healthy living environments *(Sveriges Miljömål, 2020).*

## 2.3 Bulltofta water treatment plant

Established in 1879, Bulltofta water treatment plant, or Bulltofta for short, obtains its water from Grevie aquifer. Approximately 20% of potable drinking water delivered to Malmö comes from Bulltofta, and the treatment plants delivers around 300 L/s water throughout the day *(VASYD (b), 2020).* Original water hardness of the groundwater is between 15 and 17 °dH, with an alkalinity of 340-420 mg/$HCO_3$/L *(Appendix table A.1).* Concentration of Mg is 16 mg/L and concentration of Ca is around 83 mg/L, both varying with around 10% uncertainty *(appendix, figure A.2).* In the water treatment plant, water hardness is reduced to 6 °dH by a softening process *(Appendix figure A.1).* The treated water has a pH of approximately 8.3 and a temperature of 10 °C *(Appendix table A.1).*

Water softening is carried out in two reactors using calcium hydroxide, imported as burned lime from Germany, at great economic and environmental cost. In 2019, importing burned lime cost 1 568k SEK for 3 465 000 $m^3$ of drinking water *(Areskoug, 2020).* The compound is mixed with the hard, lime-rich groundwater, and the subsequent reaction frees lime, which attaches itself to small grains of sand. The added weight of the lime makes the sand heavier, allowing it to sink to the bottom of the reactor. The sand is then removed from the process *(Appendix A.1 and table A.1).*

## 2.4 Current methods

Several methods are currently used for decreasing water hardness and some of these methods are still in use simply because they have been around for a long time. Amongst these methods, lime softening *(Bergman, 1995)* and cation exchange *(Scherer, 2017)* are common.

### 2.4.1 Lime softening

Hydrated calcium oxide or lime and sodium (Na) carbonate, are commonly used in this process. The chemicals increase precipitation of Ca and Mg carbonates, reducing water hardness. The water is balanced to diminish post-precipitation of the lime, and must be stabilised in order to control corrosivity *(WHO, 2010).* One of the bigger drawbacks with this method, is the large amounts of liquid sludge produced as waste. The softened water is also in need of re-carbonation *(Sepehr, 2013).* The method of using lime for water softening is the one currently used at Bulltofta water treatment plant.

### 2.4.2 Ion exchange

Typically, $Na^+$ is used as exchange ion, and coated on the exchange medium. This exchange medium can be either zeolites[1] or synthetic resin beads[2] resembling wet sand. Hard water passes through a softener, with $Na^+$ trading places with $Ca^{2+}$ and $Mg^{2+}$. After this trading, the exchange medium is coated with $Mg^{2+}$ and $Ca^{2+}$ and must be recharged or regenerated *(Scherer, 2017).*

Water having gone through a cation exchange softening process is not necessarily corrosive, despite its high level of Natrium chloride (NaCl). However, the water must go through stabilisation and corrosion reduction treatments, before being able to be distributed *(WHO, 2010).*

[1] Crystalline solid structures made of silicon, aluminium and oxygen. They form a framework with cavities and channels which cations, water and/or small molecules can occupy *(Peskov, 2020)* .

[2] Small porous and round plastic beads, with fixed negative ion charges *Puretec, 2020.*

# Chapter 3

# Method

## 3.1 Approach

The report is divided into three parts, with the first being a literary study based on previous research, investigating three sustainable alternatives with a potential for water softening. Information is gathered through Lund Universities Libraries (LUB), google scholar and websites with a focus on scientific research, such as Elsevier and delimitations are made at this stage of the report. To be considered potential sustainable alternatives, research must result in adsorption of $Ca^{2+}$ and $Mg^{2+}$ by tested adsorbent. Material used as adsorbent must be found in nature (plant biomass, pumice stone) or available in large amounts (plastic). Due to time constraints, the literary study is narrowed down to include only three potential alternatives for sustainable softening. Summarised results are then input in graphs and tables, to be used in the second part of the report.

The second part looks at theoretical calculations for the adsorbents. Using a mathematical approach, it aims to provide answers on amounts required for each alternative to theoretically soften the water at Bulltofta, and subsequent cost estimations. Delimitations are made regarding economic calculations, only taking into account the cost of an unmodified adsorbent. Potential costs for chemicals, alterations or modifications are thus omitted, due to the theoretical approach and lack of time for the design of practical experiments. All calculations in the report are theoretical and should be experimentally validated as part of the full evaluation of these different materials.

In the third part of the report, potential environmental impact for each suggested alternative is investigated. Using the Swedish environmental code, European laws, regulations and rules, legal and environmental requirements for softening water at Bulltofta are looked into. Other environmental effects, such as the Swedish environmental goals and $CO_2$ release are also considered.

The final analysis and overall conclusion in chapter 7 aims to summarise the results of these three parts, to answer the initial questions from *chapter 1.2*. More importantly, it allows the reaching of a conclusion on potential use of suggested sustainable alternatives at Bulltofta. Throughout the writing process, attempts have been made to contact researchers from experiments described in chapter 4, to obtain a clearer understanding of the feasibility of applying these sustainable alternatives for water softening at Bulltofta.

## 3.2 Relevance

This project is relevant for Bulltofta and Swedish drinking water treatment plants, as it could discover more sustainable and economical methods for reducing water hardness without the use of chemicals. If positive, the results could give Bulltofta an advantage in new water softening methods.

# Chapter 4

# Current research on alternatives considered for sustainable softening

## 4.1 Plant Biomass

Biomass is defined as forestry, purposely grown agricultural crops, trees and plants, organic wastes and agricultural, agro-industrial and domestic wastes. It is estimated that worldly production of biomass approaches 146 billion metric tons a year, mostly stemming from wild plant growth *(Balat and Ayar, 2005)*.

### 4.1.1 Sugarcane bagasse

Sugarcane bagasse is the biomass left after cleaning, preparation and extraction of sugarcane juice *(Rabelo et al., 2015)*. Made up of around 50% cellulose, 27% polyoses, and 23% lignin, the bagasse possesses primary and secondary hydroxyl groups (found in cellulose and polyoses), as well as hydroxyl phenolic groups (found in lignin). These groups may be used to attach certain functional groups with a selectivity for adsorption of $Ca^{2+}$ and $Mg^{2+}$. A study from Brazil investigated how sugarcane bagasse, in the study abbreviated EMMB, grafted with ethylenediaminetetraacetic dianhydride (EDTAD) [1], adsorbs $Ca^{2+}$ and $Mg^{2+}$ from aqueous solutions *Karnitz et al., 2010)*.

In the experiment, 50 mg EMMB was added into 250-mL Erlenmeyer flasks containing 50.0 mL of different concentrations $Ca^{2+}$ or $Mg^{2+}$. Ion adsorption capacity, based on the variables of time and pH was looked at. Concentrations of $Mg^{2+}$ and $Ca^{2+}$ depended on the variable chosen for the experiment, and results found EMMB to be an effective adsorbent for $Ca^{2+}$ and $Mg^{2+}$ in aqueous single solutions. Maximum adsorption capacity was noted to be around 54.1 mg/g adsorbent for $Ca^{2+}$ and 42.6 mg/g adsorbent for $Mg^{2+}$ at pH 10 and 9 respectively, as seen in *table 4.1 (Karnitz et al., 2010)*.

[1] Two anhydride groups, able to react with hydroxyl and amino groups *Sigma-Aldrich,2020)*

Table 4.1: *Maximum adsorption capacity ($Q_{max}$) at different pH. Adapted from table 3 in Karnitz et al. (2010)*

| Metal ion | pH | $Q_{max}$ (mg/g) |
|---|---|---|
| $Ca^{2+}$ | 5.5 | 46.1 |
| $Mg^{2+}$ | 5.5 | 23.5 |
| $Ca^{2+}$ | 10 | 54.1 |
| $Mg^{2+}$ | 9 | 42.6 |

Minimum adsorption capacity for $Ca^{2+}$ was recorded at pH 2.7, with maximum adsorption capacity at pH 7.5. For $Mg^{2+}$ minimum adsorption was noted at pH 3, and highest at pH 10. For the EMMB solution to reach adsorption equilibrium, it took between 10 to 50 min. The conclusion was that pH value has an effect on adsorption capacity of EMMB *(Karnitz et al., 2010)*.

Another experience from Jigjiga city in Ethiopia investigated how sugarcane bagasse, in this case treated with alkali, could be used to soften water. An original concentration of 120 mg/L Mg or Ca, mixed with 2 g of adsorbent in 1 L water, resulted in adsorption of 97% of Ca and 90.8% of Mg. Time of contact between adsorbant and ions played a role in adsorption capacity (AC) *(figure 4.1 and 4.2) (Ayaliew,2015)*.

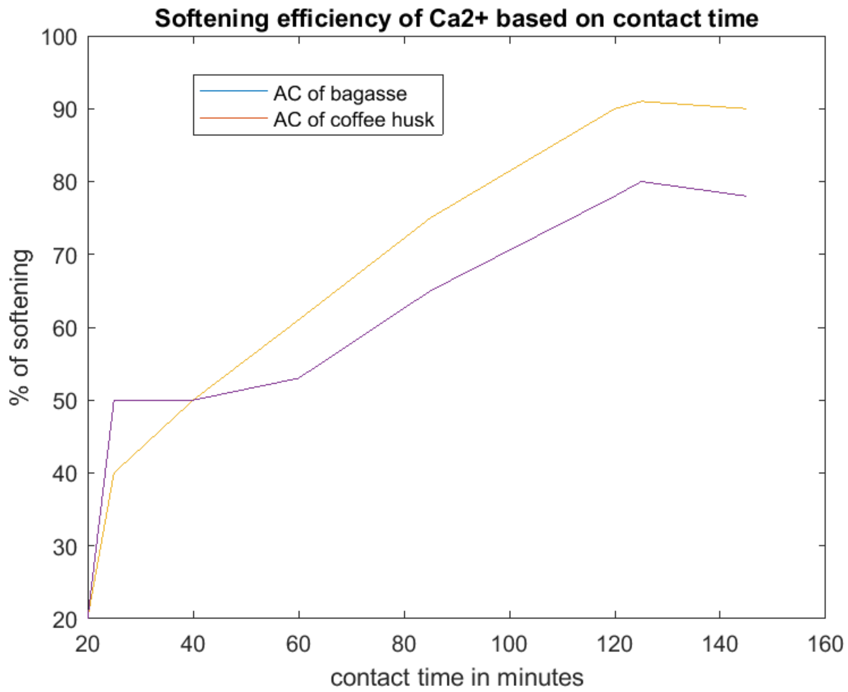



Figure 4.1: *Approximated effects of contact time on softening efficiency of $Mg^{2+}$, at room temperature and pH 6.5 at initial concentration of 120 mg/L. Adapted from Ayaliew, 2015.*

Regeneration capacity of sugarcane bagasse was also looked at, to investigate long term adsorption capacity. Using a solution of sulphuric acid, 78% Ca and 73% Mg where recovered in regeneration attempts. Although having high adsorption capacity for $Ca^{2+}$ and $Mg^{2+}$, regeneration potential decreased drastically after 8 cycles *(Ayaliew, 2015)*.

### 4.1.2 Coffee husk

Coffee husk, like sugarcane bagasse, possesses several functional groups with a capacity for binding water hardness agents. The experiment by Werkneh and colleagues in 2015 used 2 g of coffee husk as adsorbant in 1 L water. Similar results as with the sugarcane bagasse were recorded. In an original concentration of 120 mg/L Ca, 94.1% was adsorbed. The same concentration Mg resulted in 93.3% being adsorbed. In both sugarcane bagasse and coffee husk, higher adsorption capacity was recorded for Ca. The experiment also found that modifying sugarcane bagasse and coffee husk with alkali improved adsorption capacity *(Ayaliew, 2015)*.

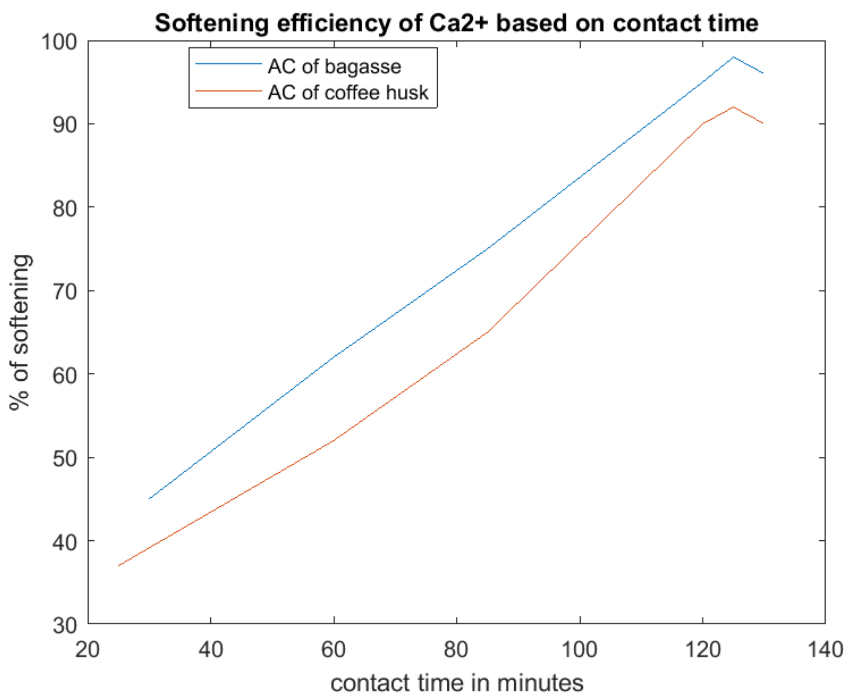



Figure 4.2: *Approximated effect of contact time on softening efficiency of $Ca^{2+}$, at room temperature and pH 6.5 and initial concentration of 120 mg/L. Adapted from Ayaliew, 2015.*

Once again, pH affects the adsorption process, impacting the degree of ionisation. Highest adsorption capacity for Ca and Mg was reached at pH 6.5. The results of softening efficiency over time for both $Mg^{2+}$ and $Ca^{2+}$ can be seen in *figures 4.1 and 4.2. Regeneration through sulphuric acid solution was higher than sugarcane bagasse, with recovery of 97% Ca and 93% Mg and a decrease in regeneration capacity after 8 cycles (Ayaliew, 2015).*

### 4.1.3 Coconut shell activated carbon

Possibilities of using coconut shell activated carbon (CSAC), made with coconut shell as base material *(Pandey et al., 200)*, has been studied. In an experiment by Cecilia Rolence et.al. *(2014)*, water samples from field collected water were used to explore possibilities of CSAC in water softening.

Collected field water had a hardness of 368 mg/L $CaCO_3$, around 21 °dH *(A.2, Appendix)*. Samples were mixed with 8 g of adsorbent in 1 L water, during 3-15 hours. Equilibrium was reached after 10 hours, and effects of pH between 2 and 12 were investigated. Adsorption efficiency was attributed to ionic strength affecting adsorption of metals. Higher ionic strength results in lower adsorption, and as field water contains several different ionic contaminants, it has high ionic strengths *(Rolence, 2014)*.

At a neutral pH of 6.3, removal efficiency of water hardness by CSAC was 44%. The removal efficiency also increased with temperature, from 29% at 303 K (30 C°) to 38% at 333 K (59 C°). Longer contact time with the adsorbents further increased removal efficiency *(Rolence, 2014)*.

As with the other experiments, pH proved important for the adsorption process. Highest removal of metal ions was recorded at pH 12, with 94% efficiency. This was deemed to be neither economical nor safe. The experiment concluded that use of CSAC showed promise for water softening *(Rolence, 2014)*.

## 4.2 Pumice stone

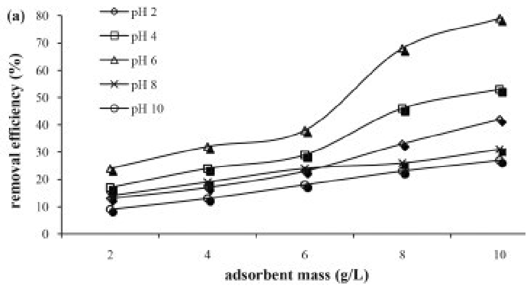
Pumice stone originates from volcanic rock, is formed from solidified frothy lava, and can adsorb up to 20-30% water. An experiment carried out in 2013 looked at the ability of pumice stone to remove Ca and Mg from water. The research looked at pumice stone in its natural state, and after being modified with alkali *(Sepehr, 2013)*.

In the experiment, three initial concentrations of $Ca^{2+}$ or $Mg^{2+}$ (50, 100 and 150 mg/L) where added to 6 g/L of natural or alkali-modified pumice, in 250 mL conical flasks. The time required for equilibrium to be reached was observed. For natural pumice samples, equilibrium was not reached after 240 min, but for alkali-modified pumice, equilibrium was reached after 150 min for $Ca^{2+}$ and 180 min for $Mg^{2+}$. In an initial metal concentration of 150 mg/L, 83% and 94% of Ca and 48% and 73% of Mg were adsorbed by natural and modified pumices respectively.

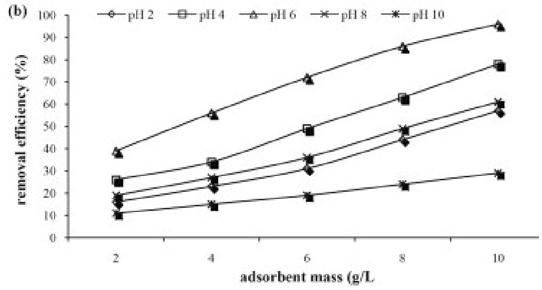
For better understanding on joint adsorption of natural and modified pumice, a solution of 100 mg/L $Ca^{2+}$ and $Mg^{2+}$ was used. Ca uptake in natural pumice was 63% and 74% for modified pumice. For Mg, natural pumice had a 27% uptake, compared to 59% from modified pumice. Both variations of the pumice stone showed higher affinity for $Ca^{2+}$ adsorption. The alkali modified pumice stone was also discovered to improve adsorption capacity of both $Ca^{2+}$ and $Mg^{2+}$ *(Sepehr, 2013)*.

The experiment found that highest adsorption capacity for $Ca^{2+}$ and $Mg^{2+}$ was at pH 6, for both types of pumice *(figure 4.3)*. Effects of temperature on Mg adsorption were deemed negligible, but a low maximum adsorption capacity for Ca was observed at 20 °C. It was concluded that the use of modified pumice stone for water softening allowed the water sample to meet required standard for drinking water in the experiment *(Sepehr, 2013)*.

Regeneration experiments were carried out in order to explore economic possibilities of this alternative. Maximum recovery of adsorbed Ca was found to be 99 % for natural pumice, and 92% for modified pumice. For Mg, regeneration capacity was 100% and 89% for natural and modified pumice stone. Natural pumice showed higher regeneration capacities than modified pumice and ion exchange was believed to be involved with the alkali-modified pumice stone, resulting in increased adsorption capacity *(Sepehr,2013)*.




(a) Natural pumice stone




(b) Modified pumice stone

Figure 4.3: Adsorption efficiency of $Ca^{2+}$ in %, using different amounts of natural (a) and modified (b) pumice stone, at varying pH *(Sepehr, 2013)*.

## 4.3 Plastic

White plastic coffee cups usually contain waste polystyrene. Considered a cheap hard plastic, they have a phenyl group attached to every carbon atom in the hydrocarbon chain. The plastic cups can be converted to adsorbents through heterogenous sulfonation[2] *(Nassef et al., 2018)*.

One experiment looked at how polystyrene could be used for water hardness reduction, by sulfonating polystyrene on the surface and keeping the core material unmodified. In turn this made the polystyrene insoluble in water, allowing the attachment of sulfonic groups to polymer chains. Through this method, the modified polystyrene could be used as resin for ion exchange in hard water *(Bekri-Abbes et al., 2008)*.

The hard water used for the experiment was prepared through dissolving 150 mg Mg or Ca into 1 L water. 50 mL of this solution was mixed with 1 g of resin from modified polystyrene. This led to the following reactions taking place:

a) $2\,ResH + MgCl_2 \longrightarrow 2\,ResMg + 2\,HCl$
b) $2\,ResNa + CaCl_2 \longrightarrow 2\,ResCa + 2\,NaCl$

Reaction a) shows how resin (ResH) binds with Mg, leaving hydrochloric acid. Reaction b) shows Ca binding to the resin (ResNa), forming NaCl as an end product *(Bekri-Abbes et al., 2008)*.

[2] A reaction consisting of the attachment of $-SO_3H$ groups on organic molecules, through the formation of covalent C-S or, less frequently, N-S bonds *(Kucera and Jancfi, 1998)*

Time and temperature affects binding capacity of Mg and Ca to modified polystyrene, differences which can be seen in *figures 4.4 and 4.5.* The resulting removal seen in the experiment proved to be somewhat higher than removal rates from natural inorganic exchangers (e.g. smectite clays), and a little lower than commercial organic resin. The research concluded that polystyrene had the capacity to bind $Mg^{2+}$ and $Ca^{2+}$, but that further research on possibilities of resin regeneration needed to be done, *(Bekri-Abbes et al, 2008).*

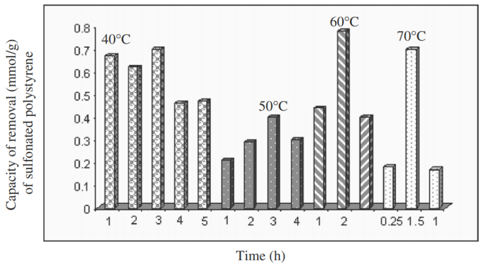



Figure 4.4: The capacity to bind Mg ions per g resin (mmol/g) over time at different temperatures. Taken from *(Bekri-Abbes et al., 2008)*

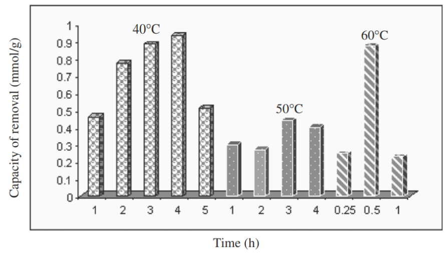



Figure 4.5: The capacity to bind Ca ions per g resin (mmol/g) over time at different temperatures. Taken from *(Bekri-Abbes et al., 2008)*

Other experiments examining the use of waste polystyrene for water hardness removal, found comparable results. *Nassef* and colleagues *(2018)* looked at maximal percentage removal of $Ca^{2+}$ and $Mg^{2+}$ for three different types of polystyrene. As waste plastic from crushed plastic cups and forks is the most relevant due to its widespread, it is the only example that will be investigated from the experiment.

Firstly, 5 g of ground and crushed polystyrene were mixed with 100 mL of dense sulfuric acid, before being mixed with water containing either 150 mg/L Ca or Mg. At a temperature of 30 °C, 68% of Mg and 47% of Ca were removed. It was noted that increasing temperature increased energy levels of involved molecules, in turn increasing maximal removal capacity of hardness ions *(Nassef et al., 2018).*

In 2011, Pentamwa et al. looked at waste polystyrene from food packaging foam and air bubble plastic. Using the Bekri-Abbes method for resin preparation, waste polystyrene was synthesised to active adsorbent resin. Hard groundwater was pumped through filter columns containing combinations of resin made from foam and waste plastic, as well as sand and gravel. A 43 % removal efficiency from the filter combinations with plastic resin was recorded, compared to 12% with no added resin *(Pentamwa et al., 2011).*

# Chapter 5

# Theoretical amounts of considered sustainable softeners at Bullotfta water treatment plant

When pumped from the ground, water at Bulltofa contains 83 mg/L Ca and 16 mg/L Mg *(Appendix, figure A.2)*. Once softened to 6°dH, the water contains 17 mg/L Ca and 15 mg/L Mg *(Appendix, table A.1)*. The softening process removes approximately 66 mg/L Ca, and in comparison, Mg adsorption is minimal. Mg will thus not be included in the following calculations. Values from chapter 4 are summarised in *table 5.1*, for use in the *equations 5.1 and 5.2* below.

To calculate the amount of adsorbant required for reducing 1 L water to its hardness of 6 °dH, *equation 5.1* is used.

$$\frac{n}{(b * x)} * y = m \tag{5.1}$$

Where:
n= amount Ca (g) removed in softening process at Bulltofta
b= adsorption percentage (%)
x= amount Ca (g) used in experiment
y= amount adsorbent (g) used in experiment
m= weight of adsorbent (g) for water softening at Bulltofta.

For calculations with EMMB *(Karnitz et al., 2010)*, *equation 5.2* is used instead. The equation is used to find out the amount of EMMB that would be required to soften 1 L of water at Bulltofta.

$$\frac{n}{x} * y = m \tag{5.2}$$

Where:
n= amount Ca (g) removed in softening process at Bulltofta
x= amount Ca (g) used in experiment
y= amount adsorbent (g) used in experiment
m= weight of adsorbent (g) for water softening at Bulltofta.

To find out the daily amount required for potential use of the sustainable alternatives at Bulltofta, *equation 5.3* is used. As the amount of adsorbent required tends to be quite large, the values are rounded of to the nearest tonne.

$$m * V = a \tag{5.3}$$

Where:
m= amount of adsorbent (g)
V= daily amount of water softened at Bulltofta (L)
a= daily amount of adsorbent (tonnes) required for softening at Bulltofta.

Table 5.1: Summary of Ca *(g)* and adsorption rate *(%)* from experiments in the literary study *(chapter 4)* and Bulltofta water treatment plant.

| **Sustainable alternative** | **n (g)** | **b (%)** | **x (g)** | **y (g)** |
|---|---|---|---|---|
| EMMB | 0.066 | - | 0.046 | 1 |
| Sugarcane bagasse | 0.066 | 97 | 0.12 | 2 |
| Coffee husk | 0.066 | 94 | 0.12 | 2 |
| CSAC[1] | 0.161 | 44 | 0.368 | 8 |
| Natural pumice stone | 0.066 | 63 | 0.1 | 6 |
| Modified pumice stone | 0.066 | 74 | 0.1 | 6 |
| waste plastic | 0.066 | 47 | 0.15 | 5 |
| plastic sand-gravel filter | 0.066 | 43 | 0.15 | 5 |

To gain a better understanding of the daily amounts required for each sustainable alternative, the obtained information has been inserted in a chart *(figure 5.1)*.

[1]The values for this row are in mg/L $CaCO_3$

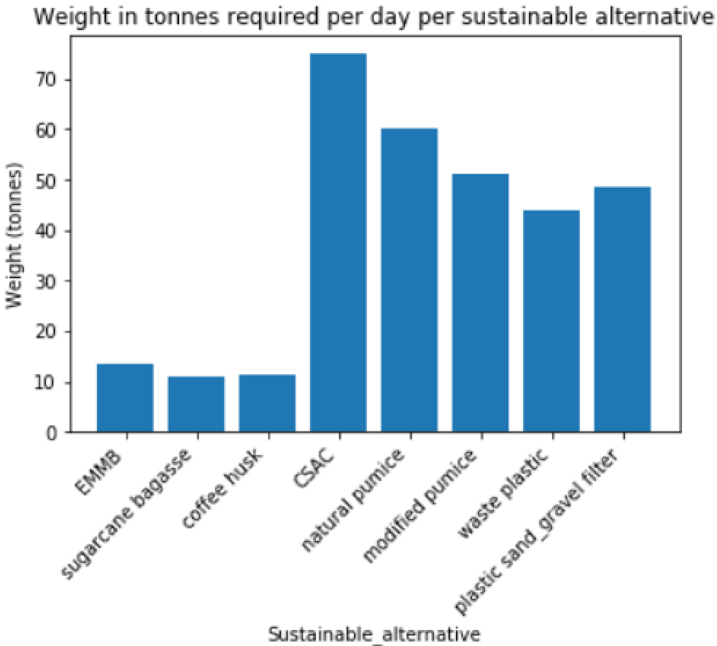



Figure 5.1: different daily doses *(tonnes)* required for softening at Bulltofta, for each sustainable alternative.

## 5.1 Plant biomass

### Sugarcane bagasse

Choosing the values recorded at least dangerous pH of 5.5, based on *table 4.1*, and inserting them into *equation 5.1*, Bulltofta would need 1.44 g EMMB/L water. For sugarcane bagasse, an adsorption of 97% of 66 mg Ca/L water would require 1.13 g of sugarcane bagasse.

In 2019, Bulltofta water treatment plant delivered 3 465 000 $m^3$ water. This would account for $3.465*10^9$/ 365= 9 493 151 L water per day. Inserting the results obtained from *equation 5.1* into *equation 5.3*, around 13.62 tonnes EMMB and 10.77 tonnes sugarcane bagasse would be needed per day for water softening at Bulltofta.

### Coffee husk

Using *equation 5.1*, the amounts of coffee husk needed for removing 94% of 66 mg Ca/L water would be 1.17g, or, using *equation 5.3*, 11.11 tonnes a day. These results are similar to the ones obtained for EMMB and sugarcane bagasse.

### Coconut shell activated carbon

In the experiment *(Rolence, 2014)*, field collected water had a hardness of 368 mg/L $CaCO_3$. Converting the water at Bulltofta from °dH to its approximate value in $CaCO_3$, would be 107.10 mg/L $CaCO_3$ at 6°dH, and 267.75 mg/L $CaCO_3$ at 15°dH, using provided data *(Appendix, figure A.2)*. This leads to a reduction of around 160.65 mg $CaCO_3$/L. The conversion from °dH to $CaCO_3$ is taken from *Appendix, table A.2* and is done through multiplication of the °dH of water hardness with 17.85 mg/L $CaCO_3$, in this case 6 and 15 °dH.

Using *equation 5.1*, it is estimated that 7.95 g CSAC would be needed to remove 44% of 161 mg/L $CaCO_3$, a low adsorption rate that would amount to 75 ton each day. To try and increase adsorption of $Ca^{2+}$, a suggestion could be to double the amount of CSAC, bringing it up to a daily weight of 151 tonnes.

## 5.2 Pumice stone

Alkali modified pumice shows higher affinity for $Ca^{2+}$ adsorption (74%), compared to natural pumice (63%). According to *equation 5.1 and 5.3*, the amount of natural pumice stone needed for Ca adsorption would be 6.30 g/L water, or 60 tonnes per day. For modified pumice stone, the results would be 5.35 g/L water, or 51 tonnes per day.

## 5.3 Plastic

The experiment *(Nassef, 2018)* showed that waste plastic removed 47% of Ca at 30 °C, requiring 4.68 g/L water of crushed waste plastic, or a daily amount of around 44 tonnes. In *(Pentamwa et al., 2011)*, a 43% adsorption of 66 mg Ca would require 5.12 g/L plastic, or 48.6 tonnes per day. Applying the same concept as with CSAC, a doubling of the weight would require 88 tonnes or 97.2 tonnes plastic respectively.

# Chapter 6

# Feasibility of applying considered sustainable softeners at Bulltofta water treatment plant

To calculate the estimated annual economic cost for each sustainable alternative, *equation 6.1* is used, setting time (t) to a fixed value of 365 days. For the daily cost of adsorbent (y), results from *equation 5.3* are converted from tonnes to kg and multiplied with the purchase cost per kg, as seen in *table 6.1*.

$$y * t = cost \tag{6.1}$$

Where:
y= daily cost of adsorbent (kr/day)
t= time (day)
cost= total cost for set amount of time, t (kr)

Table 6.1: Amount of adsorbent *(kg)* and cost *(kr/kg)* for each adsorbent, to be used in *equation 6.1* for economical calculations.

| **Sustainable alternative** | **Amount adsorbent (kg)** | **Cost kg/adsorbent (kr)** |
|---|---|---|
| Rapeseed | 13 600 | 1.2 |
| Active carbon | 151 027 | 41 |
| Natural pumice stone | 59 671 | 8 |
| Plastic | 44 436 | 150 |

## 6.1 Plant biomass

Laurent Frederic Gil informed in an email correspondence, that the purpose of the experiment had not been to investigate water hardness removal. Nonetheless, the fact that $Mg^{2+}$ and $Ca^{2+}$ are able to be adsorbed by sugarcane bagasse remains.

In plant biomass, all experiments focused on plants non-native to Sweden. As the main purpose of this report is to look at alternatives for reducing cost and environmental impact on the water softening process at Bulltofta, these are not viable alternatives. Further experiments and research should be carried out, looking at locally produced biomass alternatives. In Scania, such an alternative could be rapeseed.

According to a paper by Vuorela et al *(2004)*, rapeseed possesses the largest amount of phenolic compounds of all oil seed plants. The rapeseed *Brassica Napus*, grown in Scania contains 48.5% cellulose and 20% lignin *(Housseinpour et al., 2010)*, somewhat less than what is found in sugarcane bagasse. Out of the 95 000 hectares used for rapeseed production in Sweden, half is located in Scania *(Karlsson, 2016)*, meaning large amounts of biomass close to Bulltofta. Due to its similar constitutions to sugarcane bagasse, rapeseed could have the possibility to bind $Mg^{2+}$ and $Ca^{2+}$. Assuming this and presuming a ratio of 1:1 sugarcane bagasse to rapeseed, calculations in this chapter will be done with rapeseed as an alternative, as seen *table 6.1.*

### 6.1.1 Environmental Impact and sustainability

At first glance the use of rapeseed could potentially decrease $CO_2$ release linked to transport of softening products to Bulltofta, compared to the the current solution. However, the large amounts of biomass required, make such an environmental benefit unlikely. The biomass also needs to be transported in a safely manner, to ensure no negative effects occur on people's health or the biological diversity. There might also be the need for new facilities, or the upgrading of existing buildings at Bulltofta, to adapt for such an alternative.

the Pilot project on plant biomass need to take the Swedish environmental code (sv: Miljöbalken 1998:808) into consideration. Environmental laws which could affect implementations of pilot projects, can be linked to hazardous environmental operations in the code, chapter 9, §1, point 1 ”solid substances”:

*Release of wastewater, solid substances or gas from soil, buildings or facilities in soil, water territories or groundwater (SFS 1998:808)*

If the use of plant biomass for water softening is classified as an environmental hazardous operation, applications for permits must be done to the Land and Environment court, in accordance with chapter 9, §8. If the project only requires notification be made, it can be done to the county administrative board, the municipality or the defence inspector for health and environment (sv: försvarsinspektören för hälsa och miljö) *Law (2017:782) (SFS 1998:808).*

The potential use of this alternative would result in waste products, unless Bulltofta water treatment plant could, according to the 15th chapter in the environmental code, §1, point 1 make sure that *"the substance or object will continue to be used"*, in which case it can be considered a by-product *(SFS 1998:808).* Otherwise, according to chapter 15, §4 of the environmental code, Bulltofta would be considered waste producers:

*"[..] who generates waste (original waste producer) and they who, by pre-treatment, mixing or other procedures change the nature of the waste or composition, law (2020:601)" (SFS 1998:808).*

In such case, Bulltofta would have to investigate how to get rid of the waste, according to chapter 15, §10 and §11a *(SFS 1998:808).*

### 6.1.2 Economical cost

A thesis from SLU written in 2007 estimated the cost of rapeseed cake [1], or rapeseed pellets at around 1.20 SEK/kg *(Krokstorp and Larsson, 2007).*

In order to reduce water hardness from 17 °to 6 °dH, calculations from sugarcane bagasse and coffee husk give an amount of biomass between 10.8 and 13.6 tonnes. As rapeseed is lower in cellulose and lignin than sugarcane bagasse, assumption is made that the larger amount of rapeseed biomass of 13.6 tonnes is required. Assuming a year is comprised of 365 days and using *equation 6.1*, the annual cost could be estimated to be around 5 957k SEK. Compared to the present yearly cost of 1 568k SEK, this alternative is more expensive.

Cost estimation for active carbon will also yield a more expensive alternative. Based on prices for 1.7 kg active carbon from PGW försäljning AB and Partaj *(PGW, 2020 and Partaj, 2020)*, a conservative cost estimation would be around 70 sek for 1.7 kg active carbon, or 41 SEK/Kg. As adsorption rate was rather low, a more efficient softening rate might be obtained if doubling the amount of CSAC obtained from *equation 5.3*, resulting in the need of 151 tonnes CSAC per day.

[1] Translated from Swedish: rapskaka

Using *equation 6.1* and doubling the amount of active carbon needed per day for Bulltofta to increase adsorption, the costs would be 2 260 125k SEK. This is far from a sustainable alternative. Furthermore, it is not known if all types of active carbon adsorb hardness ion, or it must be made from base materials not common in Sweden.

### 6.1.3 Conclusion

At first glance, plant biomass alternatives are more expensive and less environmentally friendly than the current solution for water softening used at Bulltofta. They do not improve the environmental goals of non-toxic and well built environment, seemingly doing the opposite. However, experiments have shown encouraging results regarding the capacity of plant biomass to remove $Ca^{2+}$ and $Mg^{2+}$ in water. As such, there is interest in moving from theory to practical experiments, especially regarding more local plant alternatives, such as rapeseed.

According to Cecilia China (previously Cecilia Rolence), writer of the paper *Water Hardness Removal by Coconut Shell Activated Carbon*, there has been attempts to use cashew nut shell activated carbon (CNSAC) to create water hardness removal filters. Through personal communication, China has said of CNSAC, that *"it behaves nearly similar to coconut shells, only that its efficiency is higher" (China, 2020).* The experiment suggested that CNSAC might remove groundwater hardness, and a filter for water hardness removal was designed, that *" may provide the much-needed solution to many people in most developing countries" (Mwakabole et al., 2020).* This could mean that local alternatives found in Sweden have the potential of being more effective than theorised in this report. More research on filters made from active carbon or plant biomass is therefore worth investigating.

## 6.2 Pumice stone

### 6.2.1 Environmental Impact and sustainability

Sweden imports pumice stone, with main import partners being China with a share of 46%, and Iceland with a share of 30% *(Trendeconomy, 2019).* This alternative would contribute to large amounts of $CO_2$ release during transportation. Natural pumice stone has been shown to have higher regeneration capacities than modified pumice, which could, over time, result in more economically and environmentally sustainable solution.

As with biomass, potential pilot projects need to take the Swedish environmental code into consideration. Laws regarding hazardous environmental operations might be applicable for this alternative (chapter 9, §1 point 1), and the same could be true for permit application (chapter 9, §8) and waste disposal (chapter 15, § 10 and §11a) *(SFS 1998:808).* Once more, the environmental goals of non-toxic and well built environment do not seem to benefit from this solution.

### 6.2.2 Economical cost

According to the website wexthuset, 18 kg of pumice stone between 2-8mm costs around 150 kr to order *(Wexthuset, 2020)*, 8 SEK/kg. Without taking into consideration modified pumice nor the potential for pumice regeneration, cost estimations for natural pumice stone would land around 174 239k SEK. This is a more expensive alternative, compared to the current annual cost of 1 568k SEK *(equation 6.1)*.

### 6.2.3 Conclusion

This is unlikely a solution that could be considered a sustainable alternative. Adsorption capacity of pumice varies depending on if pumice stone has been modified with alkali or not, and such a modification would further increase economical costs. The large amounts of pumice stone which would have to be imported from China and Iceland, would result in the release of large amounts of $CO_2$, and Swedish environmental goals would not be further advanced by this alternative. The greatest interest with using pumice as a water softener would lie in its regeneration capacities.

## 6.3 Plastic

### 6.3.1 Environmental Impact and sustainability

In 2016, it was estimated that Sweden produced 1 258 000 tonnes plastic waste *(Nordin and Westöö, 2019)*. Annual estimations for Sweden's consumption of single use plastic cups, place the numbers between 500 to 100 millions cups *(Sanne, 2020)*. This implies that large amounts of single used plastics are available in Sweden, from which resin used for water softening could be created.

As with the previous two alternatives, pilot projects would have to look at hazardous environmental projects, permits and waste disposal *(SFS 1998:808)*. This alternative would also have to consider the new directive *(EU) 2019/904*, banning the use of single plastics and including a series of measures to be introduced for managing effects of single use plastic on the environment. The directive is intended to be put in use on July, 2021 *(Nordin and Westöö, 2019)*. Additional problems, such as microplastics in water would have to be investigated, as it could have negative effects on the environments. Like the other alternatives, buildings for storing of the plastic and water softening might also have to be built or modified.

### 6.3.2 Economical cost

Assuming that one plastic cup of 21cl weight 4 g *(Tingstad, 2020)*, around 250 plastic mugs would be required for 1 kg of plastic. For the calculation, it will be assumed that Bulltofta would pay around 150 SEK for 250 single use plastic cups[2]. Using the adsorption rate with most efficiency for hardness ion adsorption, at 47% *(5.1)*, Bulltofta would need around 44 tonnes single use plastic cup. Using *equation 6.1*, this would bring annual costs of water softening to around 2 432 871k SEK. This cost estimation is for waste plastic with a low adsorption rate and if the concept of doubling the weight adsorbant is applied, the actual cost would be much higher.

### 6.3.3 Conclusion

If this solution was to be considered, the directive (EU) 2019/904 should be observed. The question on waste production should also be addressed. Should Bulltofta pay to obtain the plastic waste, or be paid to "dispose of it"? Like the previous alternatives, non-toxic and well built environment do not seem to currently benefit from the proposed alternative.

The papers mentioned in this report have found plastic resin to have adsorption capacities on the lower end, 43 and 47%. As mentioned by *Pentamwa et al.*, removal efficiency might increase, with for example, the use of sand-gravel filters. However, an adsorption removal of less than 50% is not ideal for the water softening needing to take place at Bulltofta. Like CSAC, the amount of plastic required might instead need to be doubled.

There is value in furthering non-theoretical research on using plastic based resin for water softening. Are there possibilities of combining resin made from plastic with other filters, such as sand and gravel filters? If plastic is to be used, other risks, such as release of microplastics into drinking water, must be thoroughly investigated.

[2]based on price from the website inkclub *(InkClub, 2020)*

Figure 6.1: Summary of the sustainable alternatives suggested for water softening at Bulltofta water treatment plant

| Sustainable alternative | Annual economic cost (SEK) | Negative environmental impact | Conclusion |
|---|---|---|---|
| Rapeseed | 5 957k | Potential hazardous environmental project<br>Permits might be required<br>Potential waste production<br>Large amounts required | Not currently feasible<br>Shows most promise<br>More expensive than current alternative |
| Active carbon | 2 260 125k | Uncertainties about what active carbon can bind Ca<br>Potential hazardous environmental project<br>Permits might be required<br>Potential waste production<br>Large amounts required | Not currently feasible<br>Shows most potential after rapeseed<br>Second most expensive alternative |
| Natural pumice | 174 239k | Large CO2 release<br>Potential hazardous environmental project<br>Permits might be required<br>Potential waste production<br>Large amounts required | Not feasible<br>More expensive than current solution |
| Plastic | 2 432 871k | Directive (EU) 2019/904 can be problematic<br>Low adsorption rate<br>Potential hazardous environmental project<br>Permits might be required<br>Potential waste production<br>Large amounts required | Not currently feasible<br>Other problems linked to alternative (e.g. microplastics)<br>Most expensive alternative |

# Chapter 7

# Conclusion

The majority of the research described in chapter 4 has been done in developing countries. This is an important factor to take into account, as differences likely exist in water treatment plants from Sweden and the countries in which the experiments were carried out. Although original water hardness in these experiments is comparable to, or even higher than the hardness levels of the groundwater used by Bulltofta, these countries might deal with lower volumes of water, have smaller treatment plants or possess different requirements regarding acceptable water hardness levels than Sweden.

The amounts of each alternative, and the economical costs required for implementation of these alternatives at Bulltofta, are much larger than the present solution. Of the alternatives explored, pumice stone seems to be the most expensive and least sustainable alternative, despite its regeneration capacities. The plastic alternative has several other problems tied to it, such as low adsorption capacity, EU directive 2019/904 and microplastics. This alternative is also the most expensive, assuming Bulltofta would have to pay to obtain the plastic cups. As seen in *table 6.1*, each of the suggested alternatives have further environmental effects which also need to be accounted for. Combined with the estimated annual cost, this strengthen the claim that none of the suggested alternatives are ready to be used at Bulltofta today.

Important to remember is that the report only provides theoretical answers, untested by scientific methods. As such, empirical evidence from practically designed experiments could provide different answers than this report. Of the three alternatives, the use of plant biomass seems the most promising and as such, could benefit from further investigation. CNSAC filters, for example, have been successfully researched on. Further exploration on Swedish alternatives, such as rapeseed, could yield positive results. If the option of plant biomass is to be further explored, variables such as time equilibrium, pH and temperature are important and must be taken into account, as they have proven to affect adsorption of $Ca^{2+}$ and $Mg^{2+}$ and Cu corrosion in water pipes. In case of further interest, research by *Cecilia China and Mwakabole et al.* should be followed with interest.

Hopefully, more research on the topic may result in simple and sustainable alternative for water softening. Answers to questions regarding sustainable development can be easier than expected, the important part is to keep on thinking outside the box.

# Chapter 8

# References

ATSDR, *Copper*, Agency Toxic Substances and Disease Registration, 2011,
- accessed 19/10/2020
https://www.atsdr.cdc.gov/substances/toxsubstance.asp?toxid=37

Areskoug, Mikael, *Personal communication*, email, 28/10/2020

Ayaliew Werkneh, A., *Removal of Water Hardness Causing Constituents Using Alkali Modified Sugarcane Bagasse and Coffee Husk at Jigjiga City, Ethiopia: A Comparative Study*, International Journal of Environmental Monitoring and Analysis, 3(1), 2015
https://doi.org/10.11648/j.ijema.20150301.12

Balat, M., and Ayar, G., *Biomass energy in the world, use of biomass and potential trends*, Energy Sources, 27(10), 2005
https://doi.org/10.1080/00908310490449045

Bekri-Abbes, I., Bayoudh, S., and Baklouti, M., *The removal of hardness of water using sulfonated waste plastic*, Desalination, 222(1–3).
https://doi.org/10.1016/j.desal.2007.01.121, 2008
*Copryright for figures obtained from RightsLink*

Bergman, R. A., *Membrane softening versus lime softening in Florida: A cost comparison update*, Desalination, 102(1–3), 1995
https://doi.org/10.1016/0011-9164(95)00036-2

Boulay Nicolle and Edwards Marc, *Role of temperature, chlorine, and organic matter in copper corrosion by-product release in soft water*, Water Research 35(3), 2001
doi : 10.1016/S0043

China Cecilia, *Personal communication*, email, 2/11/2020

Dartmann, J., Sadlowsky, B., Dorsch, T., Johannsen, K., *Copper corrosion in drinking water systems - Effect of pH and phosphate-dosage*, Materials and Corrosion 3(61), 2010
doi = 10.1002/maco.200905241

Dietrich Andrea M., Glindemann, D., Pizarro, F. , Gidi, V. , Olivares, M., Araya, M., Camper Anne, Duncan, S., Dwyer, S., Whelton Andrew J., Younos, T., Subramanian S. , Burlingame Gary A., *Health and aesthetic impacts of copper corrosion on drinking water*, Water Science and Technology, 49(2), 2004
Doi: 10.2166/wst.2004.0087

Fawell, J.K., Lund, U., Mintz, B., Galal-Gorchev, H., Helmer, R., Bonnefoy, X., Espinoza, O., *pH in Drinking-water, Background document for development of WHO Guidelines for Drinking-water Quality*, 2004
https://www.who.int/water_sanitation_health/dwq/chemicals/ph.pdf

Gil L. F, *Personal communication*, email, 26/10/20

Glavič Peter and Rebeka Lukman, *Review of sustainability terms and their definitions*, Cleaner production15(18), 1875—1885, 2007

Housseinpour, R., Jahan Latibari, A., Farnood, R., Fatehi, P., Javad Sepiddehdam, S., *Fiber morphology and chemical composition of rapeseed (Brassica napus) stems*, IAWA Journal, 31(4), 2010
https://doi.org/10.1163/22941932-90000035,

Karlsson, A.-M., *Rapsen vinner*, Jordbruksverket, 2016
- accessed 25/11/2020
https://jordbruketisiffror.wordpress.com/2016/08/16/rapsen-vinner/

InkClub, *Kaffekopp plast 21 cl brun/vit, 50 st*
- accessed 3/12/2020
https://www.inkclub.com/se/sv/Kontorsmaterial/Kök-och-städ/Servering/Kaffekopp-plast-21-c/p/7322540199390?utm_source=tradedoublerse&utm_medium=affiliatemarketing&utm_content=productfeeds&utm_campaign=506.tdse

Karnitz, O., Gurgel, L. V. A., and Gil, L. F., *Removal of Ca(II) and Mg(II) from aqueous single metal solutions by mercerized cellulose and mercerized sugarcane bagasse grafted with EDTA dianhydride (EDTAD)*, Carbohydrate Polymers, 79(1), 2010
https://doi.org/10.1016/j.carbpol.2009.07.048

Krokstorp, M., and Larsson, M., *Produktionskostnad och marknadsföring av rapsolja/Cost of production and marketing of rapeseed oil*, Sveriges Lantbruksuniversitet (SLU), 2007
https://stud.epsilon.slu.se/12893/1/krokstorp_m_larsson_m_171121.pdf

Kucera, F. and Jancfi, J., *Homogeneous and Heterogeneous Sulfonation of Polymers: A Review*, Polymer engineering and Science, 38(5), 783, 1998

Livsmedelsverket (a), *Distribution*
- accessed 01/10/2020
https://kontrollwiki.livsmedelsverket.se/artikel/357/distribution#Beräkna hårdhet

Livsmedelsverket (b), *Koppar*
- accessed 25/09/2020
https://www.livsmedelsverket.se/livsmedel-och-innehall/oonskade-amnen/metaller1/koppar#: :text=Det finns ett gemensamt gränsvärde,anses vara tjänligt med anmärkning, accessed 25/09/2020

LiverTox, *Clinical and Research Information on Drug-Induced Liver Injury, Bethesda (MD): National Institute of Diabetes and Digestive and Kidney Diseases*,
National Center for Biotechnology Information-NCBI, 2017
- accessed accessed 19/10/2020
https://www.ncbi.nlm.nih.gov/books/NBK548090/

Max Peskov, *Zeolites. Atomic Scale Design Network (ASDN)*, 2020
https://asdn.net/asdn/chemistry/zeolites.php#: :text=Zeolites are crystalline solids structures,referred to as molecular sieves

Mwakabole, E. C., Rwiza, M. J., and Njau, K. N., *Column design for groundwater hardness removal using cashew nut shells activated carbon with potential application in low-income communities*, Desalination and Water Treatment, 174, 2020
https://doi.org/10.5004/dwt.2020.24857

McNeill, Laurie S. and Edwards, Marc, *The importance of temperature in assessing iron pipe corrosion in water distribution systems*, Environmental Monitoring and Assessment 77(3), 2002
doi: 10.1023/A:1016021815596

Nassef, E., Mousa, M., Elgayar, D., and Hussein, M., *A Novel Technique for Water Hardness Removal by Using Polystyrene*, Australian Journal of basic and applied sciences, 7(12), 126–138, 2018
https://doi.org/10.22587/ajbas.2018.12.7.20

NODAVA, *Vattnets hårdhet*, 2020
- accessed 19/10/2020
http://www.nodava.se/?q=node/25

Nordin H. L., and Westöö A.-K, *Plast I Sverige fakta och praktiska tips*, 2019

Oram, Brian, *The pH of water*, Water Research center
- accessed 30/10/2020
https://water-research.net/index.php/ph,

Park, Ji-Suk and Song, Jung-Hoon and Yeon, Kyeong-Ho and Moon, Seung-Hyeon, *Removal of hardness ions from tap water using electromembrane processes*, Desalination 202(1-3), 1-8, Elsevier, 2007

Partaj, *Aktivt kol*
- accessed 20/11/2020
https://www.partajshop.se/sv/artiklar/tobak-hembryggning-/aktivt-kol/index.html?gclid=CjwKCAiAuoqABhAsEiwAdSkVVAZ8d5NFGQHin0EnmiLkvy8oeKJeaCV6f6eacPnd5dMny8cPvNeIqBoCnzgQAvD_BwE

Pandey, A., Soccol, C. R., Nigam, P., Brand, D., Mohan, R., and Roussos, S., *Biotechnological potential of coffee pulp and coffee husk for bioprocesses*, Biochemical Engineering Journal, 6(2), 153–162, 2000
https://doi.org/10.1016/S1369-703X(00)00084-X

Pentamwa, P., Thipthara, W., and Nuangon, S., *Removal of Hardness from Groundwater by Synthetic Resin from Waste Plastics*, International Journal of Environmental Science and Development, 2011
https://doi.org/10.7763/ijesd.2011.v2.173

PGW, *Aktivt kol PGW 20x40. 1.7 liter*
- accessed 20/11/2020
https://www.pgw.se/hembryggning/aktivt-kol.html ,

Puretec , *Basic of water Softening*, Puretec Industrial water, San Diego, 2020
https://puretecwater.com/downloads/basics-of-water-softening-by-ion-exchange.pdf

Rabelo, S. C., Costa, A. C. da, and Rossel, C. E. V., *Industrial water recovery (Academic Press (ed.)*; Chapter 17), ScienceDirect, 2015
https://reader.elsevier.com/reader/sd/pii/B9780128022399000177?token=98D40C5154484F42E5D71C054359C907E9401B57DABA2D1013BA9F481EADC8115B5DDA1BFA343B63B61EA17AB9A6BF47

Rolence, C.,*Water Hardness Removal by Coconut Shell Activated Carbon*, International Journal of Science, Technology and Society, 2(5), 2014
https://doi.org/10.11648/j.ijsts.20140205.11

Roy, S., Coyne, J. M., Novak, J. A., and Edwards, M. A, *Flow-induced failure mechanisms of copper pipe in potable water systems*, Corrosion Reviews, 36(5), 449-481, 2018
*Copyright provided through copyright clearance center and email permission from Roy S.*

Sanne Karin, *Livscykelanalys av engångsmuggar*, IVL Svenska Miljöinstitutet
- accessed 2/12/2020
https://www.ivl.se/vart-erbjudande/referenscase/livscykelanalys-av-engangsmuggar.html

Scherer, T, *Water Softening (Ion Exchange)*, North Dakota University, 2017
https://www.ag.ndsu.edu/publications/home-farm/water-softening-ion-exchange#: :text=In the ion exchange process,exchange medium in the softener.&text=As hard water passes through,by calcium and magnesium ions

Sengupta, Pallav , *Potential health impacts of hard water*, International journal of preventive medicine , 4(8), 866, Wolters Kluwer–Medknow Publications, 2013

Sepehr, M. N., Zarrabi, M., Kazemian, H., Amrane, A., Yaghmaian, K., and Ghaffari, H. R., *Removal of hardness agents, calcium and magnesium, by natural and alkaline modified pumice stones in single and binary systems*, Applied Surface Science, 274, 2013
*Copyrights for figures obtained through RightsLink*

Sigma-Aldrich, *Conversion table*, 2017
- accessed 22/10/2020
https://www.sigmaaldrich.com/content/dam/sigma-aldrich/docs/Sigma-Aldrich /General_Information/1/conversion-tables.pdf, 2017

Sigma-Aldrich, *Ethylenediaminetetraacetic dianhydride*, Safety Sheet
- accessed 10/10/2020
https://www.sigmaaldrich.com/catalog/product/aldrich/332046?lang=en&region=SE#: : text=Ethylenediaminetetraacetic dianhydride (EDTAD) is a,used as a chelating agent

SFS 1998:808, *Miljöbalken*, Miljödepartementet
https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/miljobalk-1998808_sfs-1998-808

Sveriges Miljömål, *Sveriges Miljömål*
- accessed 19/2020
https://www.sverigesmiljomal.se/miljomalen/

Tingstad, *Produktbeskrivning platsmugg vit combi 21 cl*
- accessed 3/12/2020
https://www.tingstad.com/se-sv/foodservice/engangsmuggar/plastmuggar

Trendeconomy, *Pumice stone; emery; natural corundum, natural garnet and other natural abrasives*, 2019
https://trendeconomy.com/data/h2/Sweden/2513

United Nations, *Envision2030 Goal 6: Clean Water and Sanitation*, United Nations Enable
- accessed 19/10/2020
https://www.un.org/development/desa/disabilities/envision2030-goal6.html

US Geological Survey, *USGC: Hardness of water*
- accessed 16/10/2020
https://www.usgs.gov/special-topic/water-science-school/science/hardness-ater?qtscience_center_objects=0#qtscience_center_objects

VASYD (a), *Hårt eller mjukt vatten?*
- accessed 19/10/2020
https://www.vasyd.se/Artiklar/Dricksvatten/Hart-och-mjukt-vatten

VASYD (b), *Bulltofta vattenverk*
- accessed 16/11/2020
https://www.vasyd.se/Artiklar/Dricksvatten/Bulltofta-vattenverk

Vattenlaboratoriet, Provuppgifter personlig communication, VASYD, email, 2020

Wexthuset, *Pimpsten 2-8 mm, 18 L*
- accessed 13/11/2020
https://www.wexthuset.com/odling/jord-odlingsmedia/jordprodukter/pimpsten-2-8-mm-18-liter?gclid=Cj0KCQjwreT8BRDTARIsAJLI0KKMGfcrYaZrcJ8rZl72zNqG9ha9rsQ576cWvVSCIET-xMNbqI58bKAaAqc9EALw_wcB

WHO, *Hardness in drinking-water: background document for development of WHO guidelines for drinking-water quality*, World Health Organization, 2010

# Appendix A

# Extended information

Table A.1: Different values Bulltofta measures in untreated hard water and softened water ready for distribution *(Areskoug, 2020)*

| | **Measurement** | **Unit** | **Results** |
|---|---|---|---|
| Untreated water | Hardness | °dH | 17 |
| | Alkalinity | mg/$HCO_3$/L | 340-420 |
| Softened water | pH | pH | 8.3 |
| | Temperature | °C | 10 |
| | Alkalinity | mg/$HCO_3$/L | 98 |
| | Hardness | °dH | 6 |
| | Calcium | mg/L | 17 |
| | Magnesium | mg/L | 15 |

Table A.2: Conversion table for total hardness in calcium, using different measurement units, from *(Sigma-Aldrich, 2017)*

| | **German degree *(°dH)*** | **Concentration $CaCO_3$ *(mg/L)*** |
|---|---|---|
| 1 German degree *°dH* | 1 | 17.85 |
| 1 mg/L (ppm) $CaCO_3$ | 0.056 | 1 |

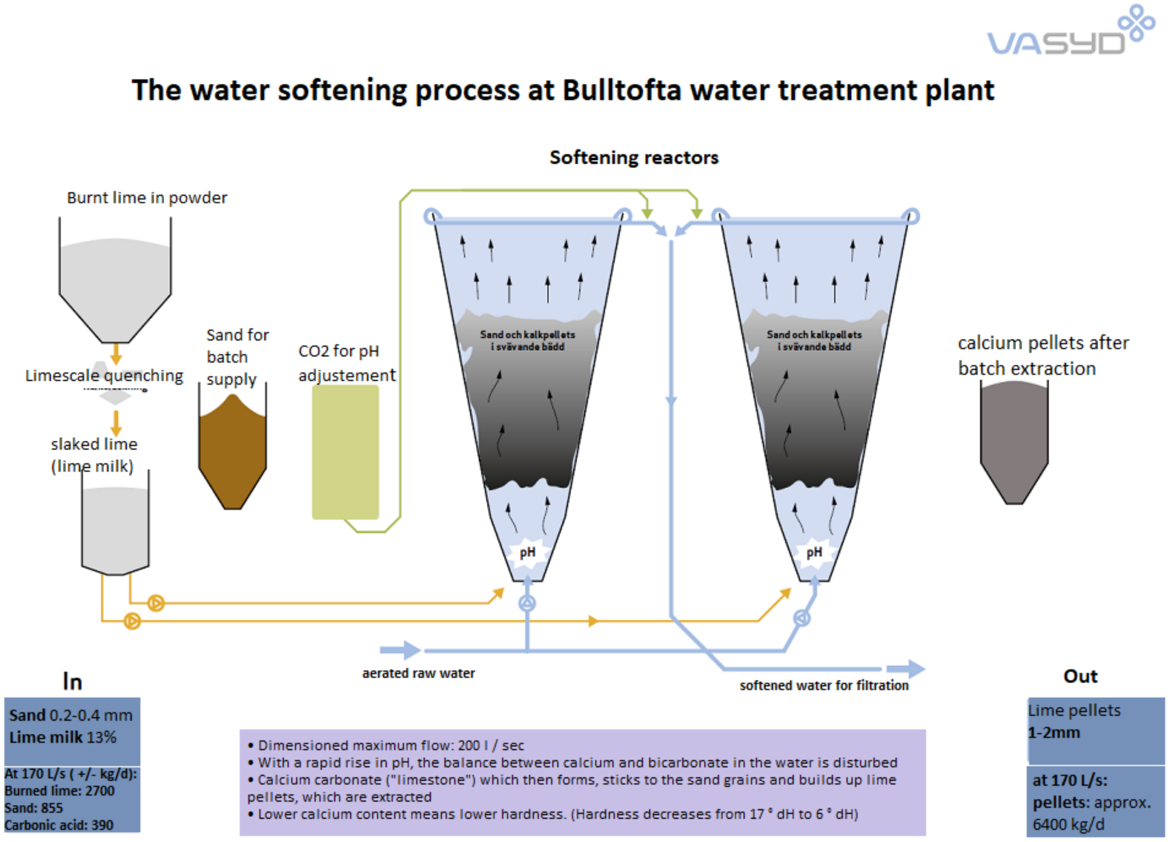



Figure A.1: Softening process Bulltofta, translated from Swedish and provided by Mikael Areskoug *(Areskoug, 2020)*

**VA SYD**
Vattenlaboratoriet

SWEDAC ACKREDITERING
Ackred. nr. 2011
Provning
ISO/IEC 17025

## RAPPORT

**Utfärdad av ackrediterat laboratorium**
***REPORT issued by an Accredited Laboratory***

| Datum | Kundnr | **Kopia** | **Sid: 1/2** |
|---|---|---|---|
| 18-03-26 | 1 | **Provnr** 18 - 330 - 1 | |

Uppdragsgivare

**VA SYD Bulltofta VV**
**VA Bulltofta**

### Provuppgifter 18 - 330 - 1

| | |
|---|---|
| Provart: | Råvatten |
| Prov start: | 18-03-07 08:30 |
| Provtagare: | Emil Pohl |
| Provet inkom: | 18-03-07 08:40 |
| Provtagningsplats: | Grevie-Bulltofta verket |
| Provmärkning: | Ink råvatten |

### Analysresultat

| | **Metod** | **18 - 330 - 1** |
|---|---|---|
| Temperatur vid provtagn* | | **9** °C |
| Temperatur vid uppackn. | | **8** ± 3 °C |
| Ansättningsdag: mikrobiologi | | **180307** |
| Mikroorganismer vid 22°C, 3 dygn | SS-EN ISO 6222, utg 1 | **1** cfu/ml |
| Koliforma bakt 37°C Colilert | ISO 9308-2 | **<1** st/100 ml |
| E-coli 37°C Colilert | ISO 9308-2 | **<1** st/100 ml |
| Aktinomyceter, 25°C (mf) | SS 028212, utg 1 | **<1** cfu/100ml |
| Färg | SS-EN ISO 7887:2012, del C | **5** mg/l Pt ± 30% |
| Turbiditet (grumlighet) | SS-EN ISO 7027, utg 1 | **59** FNU ± 15% |
| pH vid 25°C | SS-EN ISO 10523:2012 | **7,4** ± 0,1 |
| Konduktivitet | SS-EN 27888, utg 1 | **76** mS/m ± 5% |
| Alkalinitet | SS-EN ISO 9963-2, utg 1, mod | **360** mg/l ± 5% |
| Lukt, styrka vid 20°C | NMKL 183, 2005 | **Svag** |
| Lukt, art vid 20°C | NMKL 183, 2005 | **Svavelväte** |
| Ammonium | SS-EN ISO 11732:2005 | **1,4** mg/l ± 10% |
| Nitrit | SS-EN ISO 13395, utg 1 | **0,014** mg/l ± 10% |
| Nitrat | SS-EN ISO 10304-1:2009 | **<0,9** mg/l ± 5% |
| Fluorid | SS-EN ISO 10304-1:2009 | **0,47** mg/l ± 10% |
| Klorid | SS-EN ISO 10304-1:2009 | **56** mg/l ± 10% |
| Sulfat | SS-EN ISO 10304-1:2009 | **16** mg/l ± 5% |
| Tot. organiskt kol, TOC | SS-EN 1484, utg 1 | **2,5** mg/l ± 5% |
| Järn | SS-EN ISO 11885:2009 | **6,0** mg/l ± 20% |
| Mangan | SS-EN ISO 11885:2009 | **0,17** mg/l ± 30% |
| Kalcium | SS-EN ISO 11885:2009 | **83** mg/l ± 10% |
| Magnesium | SS-EN ISO 11885:2009 | **16** mg/l ± 10% |
| Totalhårdhet,beräknad | SS 028121, utg 2 | **109** mg/l ± 10% |
| Totalhårdhet,beräknad | SS 028121, utg 2 | **15** ± 1 °dH |
| Kalium | SS-EN ISO 11885:2009 | **2,8** mg/l ± 15% |
| Natrium | SS-EN ISO 11885:2009 | **34** mg/l ± 10% |
| Strontium | SS-EN ISO 11885:2009 | **3,4** mg/l ± 30% |

**Utlåtande och upplysningar**
**18 - 330 - 1**
RÅVATTEN: INGEN BEDÖMNING.

Laboratorier ackrediteras av Styrelsen för ackreditering och teknisk kontroll (SWEDAC) enligt svensk lag. Den ackrediterade verksamheten vid laboratorierna uppfyller kraven i SS-EN ISO/IEC 17 025 (2005). Denna rapport får endast återges i sin helhet, om inte utfärdande laboratorium i förväg skriftligen godkänt annat.
Den rapporterade osäkerheten är beräknad med täckningsfaktor k=2. Analyser som ej omfattas av ackrediteringen är märkta med asterisk (*).
*Laboratorier verksamma inom mikrobiologisk analys skall ha definierat mätosäkerhet för analyserna. Dessa lämnas på begäran.*

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Figure A.2: Test samples on water composition *(Vattenlaboratoriet, 2018)*