Institute of Brewing & Distilling

Received: 23 March 2012 Revised: 17 April 2012 Accepted: 17 April 2012

(wileyonlinelibrary.com) DOI 10.1002/jib.18

125th Anniversary Review: Water sources and treatment in brewing

Michael Eumann* and Stefan Schildbach

At one time the raw water naturally available influenced the development of typical regional beer styles. With the development of reliable and efficient water treatment technologies, breweries became independent of the local raw water quality. The proliferation of large breweries is still closely linked to progress in water treatment. The prevailing question is always how to best condition the raw water for the different purposes within the brewery in the most efficient way. The raw water starting points are very different and can range from well water, to surface water, to municipal water, and in some cases to more exotic water sources such as rain or even treated wastewater. The impact of different water ions on the brewing process is discussed, with a special focus on technological requirements, as well as microbiology and corrosion issues. The requirements of divergent water types commonly used for brewing, dilution, service and boiler feed water, and available treatment steps based on examples of large-sized plants are discussed, including traditional methods such as lime softening and ion exchange, as well as more recent treatment systems. Membrane technology is highlighted, as it has had a great impact on treatment technology. Following the success story of reverse osmosis, and more recently developed ultrafiltration, there is now more focus on special applications such as the substitution of lime saturators to produce clear lime water with membranes. This requires higher performance and robustness of the membranes. Finally, some future challenges for water treatment in breweries are outlined. Copyright © 2012 The Institute of Brewing & Distilling

Keywords: brewing; membranes; sources; treatment; water

1886
2011
IBD
Celebrating 125 years

Introduction

Not only is water the main constituent of beer, but its availability has become more and more a location criterion, especially for large-capacity breweries. This indicates the importance of water supply and treatment. Fortunately progress in water treatment technology has allowed the use of water sources previously not regarded as suitable for brewing purposes. The aim of water treatment can be defined as providing water of the required quality and in sufficient quantity for the different purposes in a brewery. Numerous different methods – new but also traditional ones – are nowadays available to fulfil this task. The goal is to combine the methods in the most efficient way to achieve a 'tailor-made' solution. In the following section, different treatment methods are introduced in more detail, highlighting their distinctive advantages and disadvantages.

Raw water sources

There are multiple water sources available, each with their own special characteristics.

Wells and springs

Underground water from wells or springs normally provides the best water quality in terms of microbiology and organics. It is important to source the water from a suitable depth to protect the water resource from direct surface influences. The capacity normally is independent of both season and rainfall. Nevertheless, the wellhead has to be especially protected in order to avoid any contamination from drilling, and well levels have to be monitored carefully to prevent drying out from overuse. There is usually strict local legislation that has to be followed in order to avoid spoilage of the whole aquifer.

Figure 1 shows the head of a water source in Switzerland. The source has been properly cased and a well chamber protects it from environmental impacts. As the water is forced to the surface by release of naturally occurring pressure, no submerged well pump was needed, which would otherwise normally be inserted into the well pipe. As water takes up minerals during its passage through the ground, the hydrogeological situation is decisive for the composition of the water.

Surface water

In contrast to underground water, surface water comes from lakes, rivers, and man-made reservoirs and dams. Thus the water

---

* Correspondence to: Michael Eumann, EUWA Water Treatment Plants, Daimlerstraße 2–10, D-71116 Gärtringen, Germany. E-mail: michael.eumann@euwa.com

EUWA Water Treatment Plants, Daimlerstraße 2-10, D-71116, Gärtringen, Germany

Figure 1. Wellhead of an underground water source in Central Europe, 120 m depth, capacity approximately 15 $m^3 h^{-1}$ (by EUWA).

is not constant in quality and quantity as seasonal changes and the occurrence of rain will have an impact on temperature and composition. Compared with underground water, surface water usually contains only small amounts of minerals and it is susceptible to organic load, as well as microbiological contamination. Figure 2 shows Lake Victoria in Tanzania, which is used as the water source for many purposes by the local industries.

Although obviously being available in large quantities, water overuse can be a significant issue and can lead to a continuous decrease in the water level and deterioration in water quality, which again increases the efforts necessary for water catchment as well as treatment.

Municipal water

Town water is already treated water, typically complying with the local drinking water legislation. Mineralization is widely diversified, depending on the water's origin. Most town water is either chlorinated or ozonated in order to protect it from microbiological recontamination. Figure 3 illustrates a typical town water intake, consisting of an isolating valve, as well as pressure reducer, and a distribution head.

Other sources

Rainwater collection in dry regions has been discussed in recent years, for example by Mewes *(1)*. Inconsistent availability is a major obstacle, allowing rainwater only to be used as an additional water source. Depending on the condition of the roofs used for collection, rainwater may contain a substantial amount of organics and consequently is vulnerable to microbiological contamination. This is further promoted by the necessity of building large reservoirs with long storage times. Laborious treatment and storage has prevented further spread of use of this water source to date.

Although still not widespread at this time, water recovery from brewery wastewater has become more attractive in recent years. Several research and development projects have investigated this approach in detail and confirmed the feasibility *(2–5)*. Sustainability targets set by major brewing companies regarding the overall fresh water to beer ratio clearly promote the trend towards the recycling of water.

Figure 2. Surface water in Africa (by EUWA).

Figure 3. Town water intake, Europe (by EUWA).

Water requirements for different purposes

Water is used for different purposes within the brewery. The requirements vary for different water types, which are listed as follows:

- filtered water;
- service water;
- brew water;
- dilution water;
- boiler feed water.

Filtered water

The minimum requirement for water used in a brewery is to be compliant with potable water standards such as the European drinking water regulations *(6)* or those of the World Health Organization *(7)*. Depending on the point of use, there may be a requirement for further standard adherence. These standards are based on the process requirements and on the integrity of the materials in contact with the water. These are affected mainly by scaling and/or corrosion.

As long as the water is not heated, filtered water is suitable for cleaning processes. Nevertheless, chloride might pose a threat to stainless steel installations, whereas different types of stainless steel react differently. Engineering standards such as the Deutsche Industrie Norm help to determine the risk of corrosion *(8)*. For the most common stainless steel used in breweries (American Iron and Steel Institute, AISI, 304), keeping the chloride concentration below 100 ppm is a good practice *(21)*.

The most important criterion is water microbiology. As breweries are food-producing companies, the application of microbiological requirements for drinking water is mandatory. Therefore, the potential of the water to form biofilms within the water installation system has to be considered as well. Disinfection is advisable.

Service water

Service water is needed for all kinds of cleaning and disinfection processes. Typical fields of application are cleaning in place processes and the cleaning of returnable bottles and kegs. As these processes, at least in part, occur at high temperature, it is necessary to limit the hardness of the service water in order to avoid unwanted precipitation. Otherwise scaling will affect heat transmission in heat exchangers, resulting in energy losses, but also will affect cleaning efficiency. The chloride level should be restricted to a maximum of 50 ppm *(8)*, as chloride promotes stainless steel corrosion, especially at high temperatures.

In order to maintain microbiological safety throughout the water storage and distribution systems, service water should be disinfected, preferably by using ClO_2. Chlorination by Cl_2 or hypochlorite is not the first choice, owing to its potential to form trihalomethanes (THMs) and chlorophenols, as described in greater detail below. Ozone also has its disadvantages, as under unfavourable conditions THMs, as well as bromate, can be formed as disinfecting byproducts. UV-disinfection, on the other hand, shows no relevant by-product formation, but does not provide any depot effect for subsequent installations. Finally, electro-chemically activated water techniques have become popular in recent years. Application of an electrical field leads to the formation of chlorine products, amongst others Cl_2, $HOCl^-$ and OCl^-, which are later used as disinfectants (= anolyte). With reference to anolyte, this behaves very much like chlorine in terms of byproducts *(9)*. Table 1 lists the requirements for service water as proposed by the authors.

Brew water

Of course, brew water is of major interest. High calcium levels are preferred, as calcium helps to lower the mash pH *(10)*; supports enzymatic activity during mashing as it functions as a co-factor, especially for the α-amylases; promotes protein precipitation during wort boiling; and, last but not least, helps to remove oxalates already present during fermentation, which otherwise would be the main cause for secondary gushing in beer *(11,12)*.

Table 1. Requirements for service water

Parameter	Limits
Fe (ppm)	<0.1
Mn (ppm)	<0.05
Turbidity (NTU)	0.0–0.5
Total hardness (ppm $CaCO_3$)	50–90
Na^+ (ppm)	0–200
Cl^- (ppm)	0–50
SO_4^{2-} (ppm)	0–250
NO_3^- (ppm)	0–25
NO_2^- (ppm)	0.0–0.1
ClO_2 (ppm)	0.05–0.2
$KMnO_4$ (ppm O_2 L^{-1})	<5
pH	6.5–9.5 (not aggressive)
THMs (ppb)	< 10
Total bacteria count, 22°C (CFU mL^{-1})	< 100
Total bacteria count, 36°C (CFU mL^{-1})	< 20
Escherichia coli (per 100 mL)	0
Coliforms (per 100 mL)	0
Enterococci (per 100 mL)	0

CFU, Colony-forming unit; NTU, nephelometric turbidity unit; THM, trihalomethane.

Magnesium acts in a similar manner to calcium, but owing to much better solubility of the corresponding salts, magnesium is not as efficient as calcium. The mash pH decrease is caused by the reaction and subsequent precipitation of the phosphates from the malt, which coincides with the release of H^+.

Bicarbonates on the anionic side are especially problematic, as they increase the mash pH. The reason is the formation of carbonic acid (H_2CO_3) from the bicarbonate and the subsequent removal from the mash as CO_2 owing to heating. During this process, bicarbonate acquires H^+ ions, which leads to the pH increase previously discussed.

The formula for residual alkalinity from Kolbach balances the contradicting effects (pH decrease by calcium and magnesium, pH increase by bicarbonates), allowing one to predict the influence of the brew water on the mash pH *(13,14)*.

The residual alkalinity according to Kolbach is:

$$\mathrm{RA} = \mathrm{TA} - \frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}/2}{3.5}$$

where RA = residual alkalinity (ppm $CaCO_3$); TA = total alkalinity (ppm $CaCO_3$); Ca^{2+} = Ca-hardness (ppm $CaCO_3$); and Mg^{2+} = Mg-hardness (ppm $CaCO_3$).

The Kolbach formula is based on normalization on an equivalent basis. Negative values of the residual alkalinity indicate a decrease of pH in the mash caused by the brew water, which is beneficial, whereas positive values forecast an increase in mash pH, in both cases, compared with the use of distilled water. According to Kolbach *(14)*, a decrease in residual alkalinity by 60 ppm $CaCO_3$ (converted units) lowers the pH in the mash by 0.1 unit. From the formula, it becomes evident that 1 meq of bicarbonate ‘spoils’ the beneficial effect of 3.5 meq of calcium and even 7 meq of magnesium *(15,16)*.

As a consequence, the ideal brew water contains calcium as noncarbonate hardness, but only small quantities of total alkalinity. Chloride levels should still be below 50 ppm to avoid corrosion risks owing to elevated temperatures, which otherwise are especially problematic in respect to the hot brew water reservoir in the brewhouse.

Sulfate, on the other hand, provides a welcome anion for balancing calcium and is only restricted by its direct impact on beer flavour, which has been described as dry or adstringent *(16)*. Nitrate has to be limited to <25 ppm NO_3^-, as otherwise the fermentation may be adversely affected *(17)*. Silica (SiO_2) is linked to the occurrence of turbidity in the beer *(18)* and hence should not exceed 25–40 ppm.

Oxidizing agents, such as chlorine in its various forms, including chlorine dioxide or ozone, should not be present in the brew water. Research results, such as those from Zürcher *(19)*, indicate that oxidation, even in the early stages such as the mashing stage, may have a negative impact on the shelf-life of the beer. The presence of chlorine in the brew water is especially hazardous, as a reaction with wort and beer ingredients can form chlorophenols, which even at extremely small concentrations cause a medicinal-type off-flavour.

Trihalomethanes are byproducts from chlorination and hence are often found when domestic water is used as a water source for supplying a brewery. As THMs are regarded as carcinogenic agents, their concentration should be limited to <10 ppb. Table 2 summarizes the requirements for brew water, as recommended by the authors.

Table 2. Requirements for brew water

Parameter	Limits
Fe (ppm)	<0.1
Mn (ppm)	<0.05
Turbidity (NTU)	0.0–0.5
Ca^{2+} (ppm)	80/70–90
Mg^{2+} (ppm)	0–10
Na^+ (ppm)	0–20
m-Alkalinity (ppm $CaCO_3$)	25/10–50
Residual alkalinity according to Kolbach (ppm $CaCO_3$)	<0
Cl^- (ppm)	0–50
SO_4^{2-} (ppm)	100/30–150
NO_3^- (ppm)	0–25
NO_2^- (ppm)	0.0–0.1
$KMnO_4$ (ppm O_2 L^{-1})	<5
pH	5.0–9.5
SiO_2 (ppm)	0–25
THMs (ppb)	<10
Total H_2S (ppb)	<5

Dilution water

Dilution water is similar to brew water, as it also results in the product, but in contrast to brew water, special attention has to be paid regarding a low Ca^{2+} level. Any increase in the Ca^{2+} level in the filtered beer will affect the Ca-oxalate equilibrium, increasing the risk of the formation of Ca-oxalate crystals, which can finally lead to an unwanted increase in beer gushing tendency. As the major amount of the Ca^{2+} from the brew water is utilized during the course of the production process (in mashing, lautering, cooking and fermentation), the Ca^{2+} level in the dilution water should be low, at least below the level in the beer being diluted. The risk of Ca-oxalate precipitation can be assessed based on the calcium and oxalate concentration. Schur *et al*. *(12)* proposed a corresponding formula including recommendations of target ranges.

The dilution water must also be deaerated in order to avoid beer oxidation. The common target value for deaeration plants nowadays is <10 ppb dissolved oxygen. As dilution water goes directly into the final product without any further treatment steps, THMs must be reduced even further, compared with brew water, with a target of <1 ppb. Table 3 provides an overview, which again reflects the recommendations by the authors.

Boiler feed water

For shell boilers, which are common in breweries, the most important requirement is to keep the boiler feed water virtually free from hardness (<1 ppm $CaCO_3$). Furthermore, the total alkalinity should be limited in order to avoid the decomposition of soda into NaOH and CO_2 in the boiler, with the released CO_2 then causing corrosion.

Furthermore, prior to use in the boiler, oxygen and carbon dioxide have to be removed. This is usually accomplished by thermal deaeration. Additional conditioning of the boiler water is necessary and consists of alkalization and the use of oxygen scavengers such as sulfite, as well as hardness scavengers such as phosphates, in order to capture traces of hardness. Legislation is based on technical norms such as the Technische Regeln für Dampfkessel *(20)*, but may be slightly different in other countries. Further requirements from the suppliers of shell boilers also require adherence. Table 4 gives an overview. The operation of steam turbines or high-speed steam generators requires completely demineralized boiler feed water.

Table 3. Analytical requirements for dilution water

Parameter	Limits
Fe (ppm)	<0.02
Mn (ppm)	<0.02
Turbidity (NTU)	0.0–0.5
Ca^{2+} (ppm)	30/20–40
Mg^{2+} (ppm)	0–10
Na^{+} (ppm)	0–20
m-Alkalinity (ppm $CaCO_3$)	25/10–50
Cl^{-} (ppm)	0–50
SO_4^{2-} (ppm)	0–50
NO_3^{-} (ppm)	0–25
NO_2^{-} (ppm)	0.0–0.1
$KMnO_4$ (ppm O_2 L^{-1})	<5
pH	5.0–9.5
SiO_2 (ppm)	0–25
O_2 (ppb)	$<10/<20$
THMs (ppb)	<1
Total H_2S (ppb)	<5

Table 4. Analytical requirements for boiler feed water (shell boilers only)

Parameter	Limits
Fe (ppm)	<0.1
Mn (ppm)	<0.05
Total hardness (ppm $CaCO_3$)	0–1
m-Alkalinity (ppm $CaCO_3$)	0–50
pH	>9.0
O_2 (ppb)	<30
Sulfite (ppm Na_2SO_3; in boiler water)	10–20
Phosphate (ppm; in boiler water)	10–20

Water treatment

Pretreatment

Apart from special points of use with only minor importance such as irrigation, water for all other applications in breweries should be of drinking water quality. Figure 4 shows a general treatment scheme.

It is important to process the water into a microbiological unobjectionable status. This can be achieved only if the water is free from particles and unstable components like iron and manganese. Iron and manganese tend to oxidize and form precipitates as soon as they come into contact with air. Therefore, the initial treatment should always include a filtration step, which is normally performed with sand or multilayer filters. For even better results, ultrafiltration has proved its capabilities in recent years. Ultrafiltration yields special advantages for treating microbiologically highly contaminated waters such as surface water. It forms a germ barrier, holding back parasites, bacteria and even viruses at a high rate, and also turbidity is removed almost completely.

Figure 5 shows an ultrafiltration plant with an output of 270 m^3 h^{-1}. The membranes in the white housings were installed in an upright position. The upright position and short modules facilitate easy backwashing and removal of retained particles and turbidity. Depending on the water quality, in most cases these are operated in a dead-end mode.

After filtration, the water should be treated with a disinfectant such as chlorine dioxide, before being stored in a filtered water reservoir. The reservoir not only provides a buffer for fluctuating water demand, but also serves as a contact tank for the disinfectant, which requires a minimum contact time for unfolding its full potential, typically 20 min.

Main treatment

The main treatment process adjusts the ionic composition of the water for the different purposes as described above. The most traditional treatment, especially suitable for brew water, is lime softening, as it lowers carbonate hardness, but keeps the noncarbonate hardness unchanged. Lime [$Ca(OH)_2$] is added, and this causes bicarbonate to be transformed into carbonate, which again is precipitated and sedimented as $CaCO_3$. In the case of high magnesium hardness, a two-stage system is

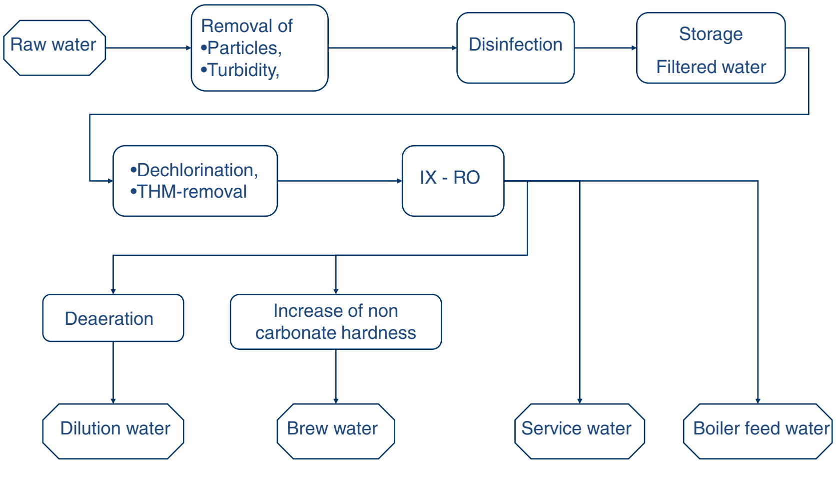

Figure 4. General treatment scheme.

Figure 5. Ultrafiltration plant in Korea, output 270 m^3 h^{-1}, recovery 95% (by EUWA).

required. Nevertheless, depending on the ionic composition, not all raw water is suitable for lime softening.

Figure 6 shows a one-stage lime softening plant, with a capacity of 150 m^3 h^{-1}. The large reactor seen in the background is where the reaction takes place. The smaller vessel attached to the reactor is the premix tank, in which water is mixed with lime milk, before the water enters the main reactor. Although providing some major advantages, such as the simultaneous removal of iron, manganese and organics, minimum wastewater, low costs for the lime needed and being a natural system without the use of chemicals such as acids, this method has fallen into disuse. The main reasons for this were the high investment costs owing to the necessity of building large reactors to provide sufficient settling time. This made lime softening a less attractive process compared with other treatments. Only recently has the chemistry of lime softening been combined with modern membrane technology, making the large sedimentation vessels obsolete and hence making the system much more attractive. The future will show whether this new approach will turn into a success.

Figure 6. One-stage lime softening plant in Germany, 150 m^3 h^{-1} (by EUWA).

Ion exchange, in its different techniques, ranges from simple dealkalization by weak acidic ion exchangers to softening with strong acidic ion exchange resins regenerated with NaCl and decationization using strong acidic ion exchange resins regenerated with acid like HCl to anionic exchange. In combination with the cationic exchange, nitrate removal or even complete demineralization and SiO_2 elimination is possible. The main disadvantage is the use of chemicals such as salt, acid and/or caustic. Apart from the necessity of handling these chemicals, they contribute significantly to the operation costs, and salt load in the wastewater is much higher compared with other technologies such as, for example, reverse osmosis. Nevertheless, water treatment based on ion exchange is a well-known and robust technology, with normally smaller water consumption compared with that of reverse osmosis.

Figure 7 shows a cation exchange plant, installed in South Africa, with a capacity of 140 m^3 h^{-1}. The exchanger vessels are made of mild steel with a rubber coating inside to protect the vessels from corrosion by the regeneration chemicals (hydrochloric acid). The exchangers are regenerated in counter-current mode for maximum chemical utilization. Five pipes are inserted horizontally in the upper half of the ion exchanger vessels and form the drainage system, through which the regeneration water is removed from the exchangers during regeneration. The piping is fabricated with high density polyethylene. Stainless steel is not suitable due to corrosion issues.

Reverse osmosis is frequently used (Fig. 8). The water is forced through polyamide membranes, using high pressure as the driving force. The pressure has to exceed the osmotic pressure.

Figure 7. Cation exchanger in Africa, 140 m^3 h^{-1} (by EUWA).

As a result, the water is demineralized to a large extent. The usual pressure applied is 7–15 bar, depending on the type of membrane used, and also on the salt concentration of the raw water, as well as the yield in the plant. Owing to the passage of pure water, the salts are concentrated on the concentrate side. Precipitation is avoided by adding anti-scalants. Waste water may become an issue, as the usual recovery of a reverse osmosis system only ranges between 80 and 90%. In an attempt to increase the yield, further pretreatments such as softening and pH adjustment, mainly with acids, is applied. Depending on the raw water quality and pretreatment, up to 95 % recovery is possible.

Figure 9 shows a reverse osmosis plant consisting of three racks with a capacity of 77 m^3 h^{-1} in each rack. The modules were inserted into the horizontal blue pressure vessels, with the pump stations on the right-hand side providing the required pressure.

Apart from the fact that brew and dilution water should be free from chlorine or chlorine dioxide, for the reasons stated above, any oxidizing agents present must also be removed from the water, prior to ion exchange or reverse osmosis, as otherwise the resins and the membranes may be damaged by oxidation. Removal can be best achieved by the use of activated carbon filters. Alternatives for dechlorination are UV-irradiation at high dose rates or dosing with a bisulfite solution.

Activated carbon filtration can further be used for the removal of unwanted organic compounds such as THMs. Owing to the large inner surface of the activated carbon and the fact that it adsorbs organics, the filters are vulnerable in regard to microbiological contamination. Thus, the activated carbon filters must be designed in a manner that allows regular

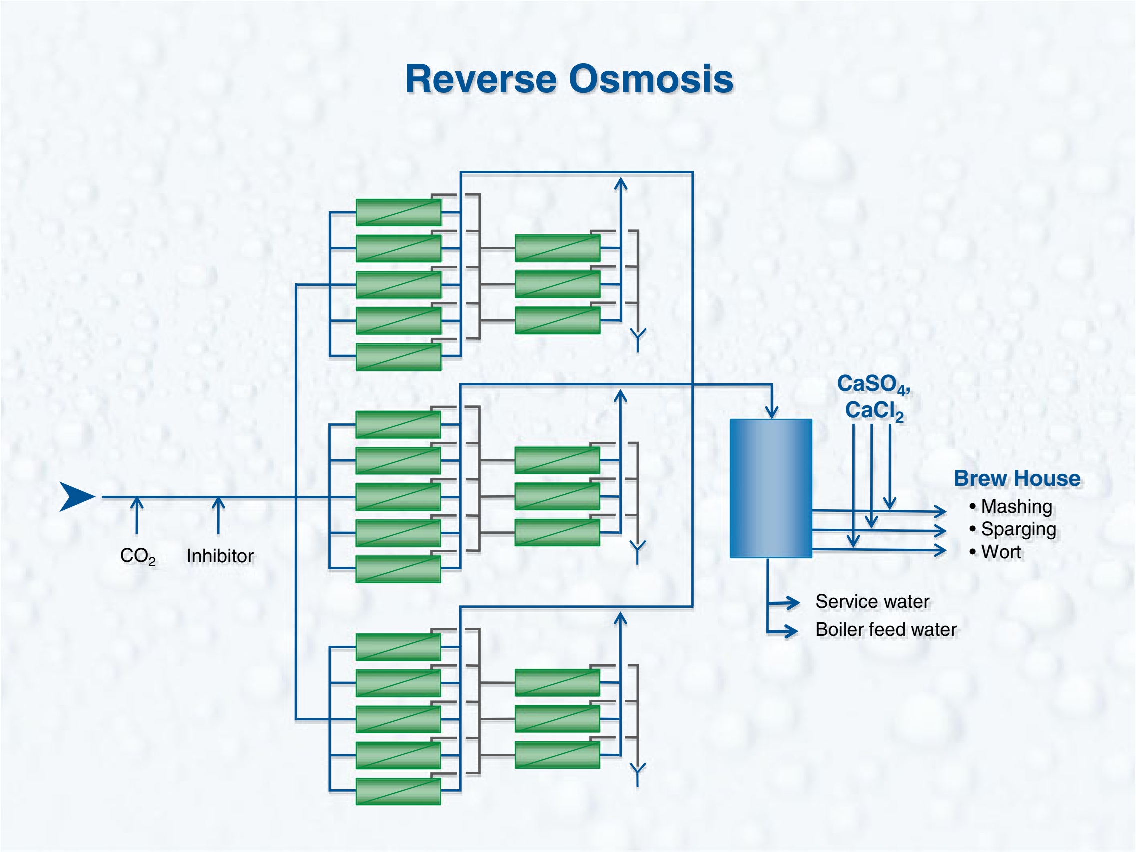

Figure 8. Schematic reverse osmosis.

Figure 9. Reverse osmosis plant in Thailand, 230 m^3 h^{-1} (by EUWA).

thermal sterilization with steam or hot water. This is typically carried out once a week.

Figure 10 shows activated carbon filters designed for THM removal with a contact time of close to 20 min. Vessels and pipe systems were fabricated out of stainless steel in order to allow regular thermal sterilization with steam.

The increase in noncarbonate hardness ($CaSO_4$ and $CaCl_2$) is essential for good brew water quality. Owing to poor solubility, the addition of $CaCO_4$ is hard to control and a messy affair. Addition of $CaCl_2$ is limited by chloride, in order to avoid stainless steel corrosion as stated above. Another approach is the dosing of H_2SO_4 and HCl into a saturated lime water [$Ca(OH)_2$], forming a concentrated solution of noncarbonate hardness, which can be added into the brew water or even directly in the brew house, allowing the individual adjustment of calcium levels and ratios of sulfate to chloride for different brands. Saturated lime water is produced out of solid hydrated lime with the help of lime saturators. A more recent approach for lime water production uses membrane technology, thus eliminating the lime saturator. Lime water quality is better (particle-free, saturated) and lime utilization is increased. The main advantage is the elimination of a large sized lime saturator, which is a major cost.

Figure 11 displays a small membrane-based lime water plant installed in Germany. The filtration module was located in the rear, whereas the defined lime milk mixing with water takes place in the pipe system in the foreground.

Figure 10. Activated carbon filtration in Korea, 285 m^3 h^{-1} (by EUWA).

Figure 11. Membrane-based lime water production in Germany, 500–1500 l h^{-1} (by EUWA).

Water deaeration nowadays can also be achieved using membrane technology. Hydrophobic hollow fibre membranes of polypropylene allow the passage of gases, but not of water. Polypropylene provides another advantage in respect to cleaning, as it is resistant towards acids and caustics, allowing cleaning in place of the plant. These membranes are not only applicable for oxygen removal, but can also be used for the removal of CO_2, in order to limit the corrosion tendency towards mild steel installations.

Figure 12 shows a deaeration plant for removing oxygen from the dilution water. The deaeration process was enhanced by the application of CO_2 and vacuum on the gas side (vacuum pump not on display).

Figure 12. Membrane-based deaeration system in Thailand, 50 m^3 h^{-1} (by EUWA).

Summary and outlook into water treatments of the future

Water treatment has undergone a number of remarkable changes in recent years, with new technologies emerging and additional water sources coming into focus. In particular, the reuse of water has been investigated intensively, with two approaches becoming more and more accepted.

One approach focuses on the closed loop principle, which means that water from a consumer within the brewery is recovered and reprocessed and then used for the same purpose as before. The manner in which the water is polluted during the process is known, thus making treatment easier.

End-of-pipe is the second approach. It focuses on the recovery of water of drinking water quality from the overall effluent of the brewery. Although pollution is much more complex and harder to treat, the amount of water that can be recovered is much larger, thus making it much easier to justify the investment in a water recycling plant.

Carrying out trials/tests and keeping in mind the ongoing efforts in defining and reaching sustainability targets set by a number of brewing companies, water treatment of the future has to provide better treated water out of deteriorating raw water, using less resources (water, energy), at lower costs, with easy-to-handle processes and superior disinfection processes with no or minimized by-products, and producing only slightly or even nonpolluted wastewater.

Water treatment will become more sophisticated, including the need for more tailor-made solutions that implement water savings and address waste water recycling. New developments in materials and technologies will improve overall performance (less energy and waste water, and even no chemicals). Furthermore, the impact on the wastewater side will be included right from the start (a holistic approach), making things more difficult on the one hand, and providing interesting opportunities, such as the recovery of valuable matter or improved energetic exploitation of the wastewater.

References

1. Mewes, V. (2011) Optimized brewery engineering, reasonable investments for a greener future. oral presentation. *VLB Brewing Conf.*, Bangkok, 14–17 June.
2. Englisch, R. (2006) Aufbereitung von Brauereiabwasser bis zur Wiederverwendbarkeit. Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen, Fakultät Maschinenwesen.
3. Eumann, M. (2011) Water recycling in breweries using the end-of-pipe-approach: latest results. Oral presentation, *2nd Iberoamerican VLB Symp. Brewing and Filling Technology*, Mexico City, 29 March to 1 April.
4. Walter, S. (2005) Untersuchung verfahrenstechnischer Möglichkeiten zur Brauchwasserkreislaufführung in der Brauerei. Dissertation, Technische Universität München, Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt.
5. Watts, S. and Keller, J. (2005) *Technical Review: Best Management Practice for Wastewater Treatment Plants and Re-Use Options in South East Queensland*. Moreton Bay Waterways and Catchments Partnership MBWCP, Brisbane.
6. EC (1998) Council Directive 98/83/EC on the quality of water intended for human consumption, *Off. J. Eur. Commun.*, *L330*.
7. World Health Organization (2006) *Guidelines for Drinking-water Quality*. First Addendum to Third Edition, Volume *1*, Recommendations, WHO: Geneva.
8. Deutsche Industrie Norm DIN EN 12502–4 (2005) Korrosionsschutz metallischer Werkstoffe – Hinweise zur Abschätzung der Korrosionswahrscheinlichkeit in Wasserverteilungs- und speichersystemen – Teil 4: Einflussfaktoren für nichtrostende Stähle, Beuth-Verlag: Berlin.
9. Kunzmann, C. (2008) Innovative Wasserdesinfektion – analytische und technologische Aspekte. Oral presentation, *95th VLB Brewing and Engineering Conf.*, Kulmbach.
10. Kolbach, P. and Schwabe, K. (1941) Über den Ausgleich der Carbonatwirkung durch den Gips des Brauwassers, *Wochenschrift für Brauerei*, *58*, 195–198.
11. Kieninger, H. (1983) Calcium und Gushing, *Brauwelt*, *123*(1/2), 14–25.
12. Schur, F., Anderegg, P., Senften, H., and Pfenniger, H. (1980) Brautechnologische Bedeutung von Oxalat, *Brauerei Rundschau*, *91*, 201–207.
13. Kolbach, P. (1941) Zur Beurteilung gipshaltiger Brauwässer, *Wochenschrift für Brauerei*, *58*(44), 231–233.
14. Kolbach, P. (1953) Der Einfluss des Brauwassers auf das pH von Würze und Bier, *Monatsschrift für Brauerei*, *6*(5), 49–52.
15. Kolbach, P. and Haussmann, G. (1933) Über den Einfluss der Erdalkalisulfate und –chloride des Brauwassers auf die Zusammensetzung der Würze, *Wochenschrift für Brauerei*, *50*(26), 201–205.
16. Kolbach, P. and Rinke, W. (1964) Der Einfluss des Magnesiumsulfats im Brauwasser auf die Zusammensetzung und Qualität des Bieres, *Monatsschrift für Brauerei*, *133*, 206–209.
17. Vogl, K., Schumann, G., and Pröbsting, W. (1967) Über den Einfluß des Nitratgehaltes natürlicher Wässer auf den Gärverlauf von Bierwürzen, *Monatsschrift für Brauerei*, *20*, 116–120.
18. Netscher, H. (1928) Die Kieselsäure im Bier, *Wochenschrift für Brauerei*, *45*, 582–585.
19. Zürcher, J. (2003) Der Einfluss des Blattkeims von Gerstenmalz auf die Geschmacksstabilität und weitere Qualitätsmerkmale von Bier. Dissertation Technische Universität München, Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt.
20. Technische Regeln für Dampfkessel (2001) Speisewasser und Kesselwasser von Dampferzeugern der Gruppe IV, TRD 611 Speisewasser.
21. ASTM A240 / A240 M-12 (2012) Standard Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications, ASTM International: West Conshohocken, PA, USA.