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Chapter 3

Resource recovery from drinking water production facilities: what and how much is there?

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3.1 INTRODUCTION

Cost-effective, reliable production and safe transportation of high-quality drinking water through a comprehensive distribution network is one of the pillars of modern society that has enabled mankind to live in densely populated cities. The greatest acute health risk when consuming contaminated water are waterborne pathogens that can lead to outbreaks of diseases which in extreme cases can result in death and can affect a large proportion of the community (Baldursson & Karanis, 2011; https://www.un.org/sustainabledevelopment/water-and-sanitation/). In addition to the safety of drinking water from a human health perspective, drinking water needs to be of a high 'aesthetic' quality in order to gain full consumer acceptance. Important aesthetics aspects include appearance, that is off-tastes, odors and staining (Hargesheimer & Watson, 1996). Considering the vital role of providing safe drinking water to our society, it is not surprising that significant efforts have been made to develop and design regulations and guidelines that offer an authoritative reference on: (i) what defines 'safe and good quality' water, (ii) how it can be achieved, and (iii) how this can be ascertained. The difference between regulations and guidelines is that the first are maintained directives while guidelines are non-mandatory standards. It should be noted that the nature and form of regulations and guidelines varies among countries and regions. Similarly, and somewhat surprisingly, there is no recognized standard that jurisdictions follow in adapting existing knowledge to their own regional context. Often this results in different safe values proposed for water quality parameters in different jurisdictions.

To ensure drinking water of good quality, the treatment process generally consists of a multi-barrier system. Its function must continuously be maintained as well as that of the clear water storage and reticulation mains. Distribution mains can be located underground or above the surface. While colder climates try to avoid freezing by burying the mains, warmer climates lay water mains above the ground. It is generally assumed that warmer waters increase the necessity for maintaining a disinfectant residual during distribution. While the primary goal of water treatment is first and

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foremost to produce high-quality drinking water, we will discuss here whether this can be achieved with concomitant recovery of resources.

While resource recovery from water has gained a lot of momentum in recent years, one often associates this with recovery of materials and resources during the treatment of domestic and/or industrial wastewater. In comparison, resource recovery from drinking water treatment plants has attracted less attention. However, there are plenty of resources to be recovered during the production of drinking water and/or during water recycling operations. In fact, resource recovery of residuals from drinking water treatment has some advantages compared to recovery of resources from domestic wastewater. The presence of pathogens, toxic metals, and microbial contamination in domestic wastewater often comes with regulatory hurdles and issues around public/customer perception and market acceptance. Certainly, technological advancement in the last decades have made it possible to overcome these quality and regulatory issues and have allowed us to recover resources from wastewater at such qualities that in some cases the quality exceeds that of virgin raw materials. Nevertheless, the importance of public/customer perception and market acceptance is something that cannot be underestimated. One can imagine that recovering products from drinking water seems something that could more easily gain full consumer acceptance.

3.2 LEARNING OBJECTIVES

At the completion of this chapter you should be able to:

- Describe water treatment and drinking water consumption and explain its potential opportunities for resource recovery.
- Describe key resources present in various sources for drinking water production that can be recovered; that is surface water, ground water, sea water and reclaimed water.
- Describe the key resources that can be recovered during the production of drinking water that are added during the water purification process.
- Understand the differences between resource recovery from wastewater and drinking water production in relation to product quality, regulatory hurdles and technology requirements.
- Understand the importance of the non-technological aspects such as creating a strong stakeholder community, effective communication and market/customer acceptance.

3.3 MAJOR SOURCES FOR THE PRODUCTION OF DRINKING WATER

There are four major sources used for drinking water production, namely surface water, ground water, seawater, and reclaimed effluent from wastewater treatment plants. Surface water sources can be lakes, reservoirs, rivers, streams or ponds. Treated effluent from wastewater treatment plants which would normally be discharged to the receiving environment can be further treated using advanced technologies to produce water at (or even) exceeding drinking water quality (see Chapters 4 and 18 for more detail). High quality (recycled) water exceeding drinking water quality is often used in industrial applications such as ultra-pure water for cooling towers in power plants or in high tech industry.

Depending on the geological location of the water treatment plants the predominant source of water used will be different (Figure 3.1). For example, due to its dry climate and limited supply of fresh water, about 40% of the drinking water produced in Israel comprises desalination of seawater and saline groundwater (Feitelson & Rosenthal, 2012). On the other hand, European countries like France, Netherlands and Germany produce as much as 70% of their drinking water from groundwater while Australia and Canada mainly rely on surface water from rivers, reservoirs and lakes. In addition, substantial regional differences within countries exist. A good example is China, where 70% of the national groundwater reserves are located in its southern part, generating a distinct regional imbalance (Liu & Zheng, 2016).

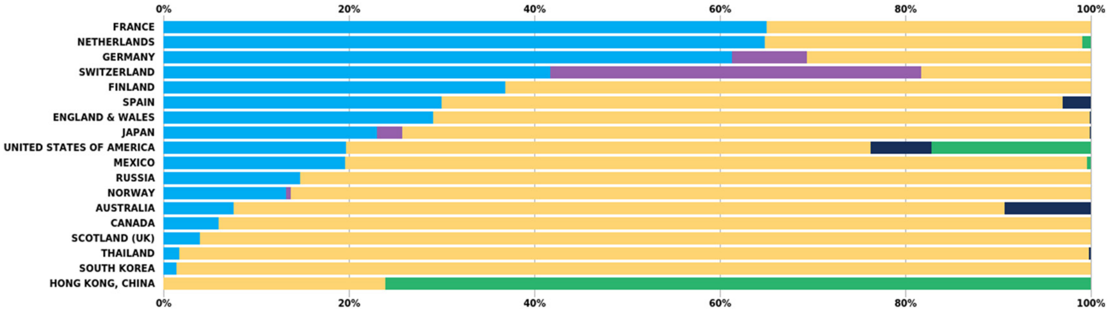

Figure 3.1 Distribution of the different water sources used for the production of drinking water (2014) (http://waterstatistics.iwa-network.org/).

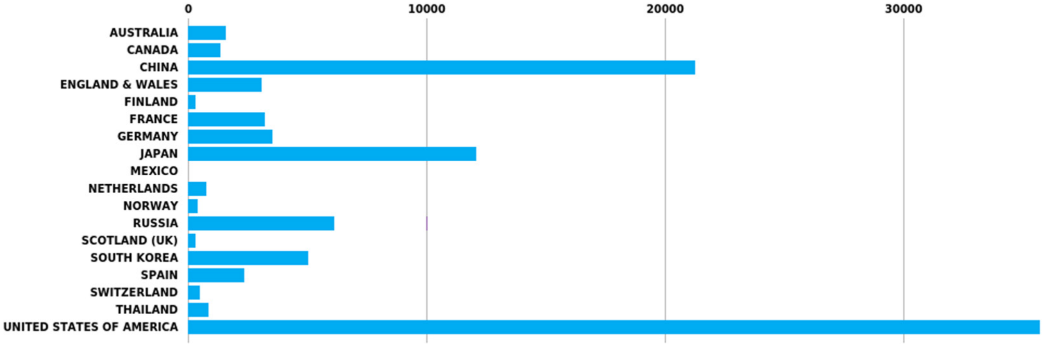

Figure 3.2 Water delivered to households and small businesses in 2014 in million m³ per year, adapted from (http://waterstatistics.iwa-network.org/).

In general, centralized water treatment is applied in major urban areas and in most parts of the developed world. This means source water is treated at a centralized treatment plant and then delivered to consumers through a pressurized distribution system. Centralized treatment plants in major urban areas produce up to several hundred thousand m^3 of drinking water per day. One could imagine that such a large scale and centralized production of drinking water in general has a beneficial impact on the potential of resource recovery due to the economy of scale. Figure 3.2 shows the volumes of water delivered in different countries per year (note: this should give a good indication on the national resource recovery potential of the countries listed). In 2016, the USA delivered the most drinking water to households and small businesses (no data available on water consumption of the industrial sector) with ~35 billion m^3. China, with a four times greater population, only produced 21 billion m^3, while European countries, including Germany and France, delivered between 3.2 and 3.5 billion m^3.

3.4 CURRENT PRACTICE IN WATER TREATMENT

In this paragraph, the most commonly used treatment processes for drinking water production are described. It is evident that the type of process selected depends on the desired production capacity and the characteristics of the water source used. It is not the aim of this chapter to discuss each process in detail, but rather to provide the reader with a general overview of these processes in relation to their resource recovery potential. To obtain in-depth process understanding, we refer the reader to textbooks where these treatment processes are discussed in great detail (Crittenden & Borchardt, 2012; Edzwald, 2010).

3.4.1 Coagulation-flocculation-sedimentation

For the coagulation process a variety of chemicals can be used. However, the vast majority of treatment plants uses either iron or aluminum-based salts as base coagulant (Pikaar *et al.*, 2014). A typical dosage ranges from 10 to 150 mg/L for aluminum sulfate ($Al_2(SO_4)_3{\cdot}14H_2O$), 10–250 mg/L for ferric sulfate ($Fe_2(SO_4)_3{\cdot}9H_2O$) and 5–150 mg/L for ferric chloride ($FeCl_3{\cdot}6H_2O$) (Crittenden & Borchardt, 2012). The chemical dosing requirements are obviously dependent on the raw water quality in terms of alkalinity, turbidity, color and natural organic matter load. The coagulation process contributes the major load of the solid water treatment residuals containing either aluminum or iron oxides 'polluted' with organic matter (i.e., mainly humic and fulvic acids), clay, silt, colloidal material, and microorganisms with other chemicals employed in the process such as a diversity of flocculants (Crittenden & Borchardt, 2012). The vast majority of these solids are then separated in a clarifier and gathered by the sludge removal system. Sometimes powdered activated carbon (PAC) is applied for the control of taste and odor compounds as well as for the sorption of emerging contaminants, which then ends up in the solid waste as well. Another source of solids is from the regular backwash of rapid media filters that further treat the effluent of the clarifier. Besides carry-over from the clarifier, solids generated by the addition of filter aid polymers and/or the oxidation of manganese and iron to insoluble forms accumulate on the filter and result in a relatively large volume of residual produced in a short time.

3.4.2 Lime-soda ash softening

Lime-soda ash and pellet softening are common methods used to reduce the hardness of source waters by precipitation that also produces a solid residual stream. These processes are preferred in waters high in calcium and magnesium where also heavy metals and radioactive elements like radon may be removed. Lime-soda ash is a precipitative process that typically includes coagulation, flocculation, and sedimentation applying quicklime (i.e., $CaO(s)$), or hydrated lime (i.e., $Ca(OH)_2$). Sodium hydroxide is used when at least half of the calcium hardness is carbonate hardness. An alternative to coagulation-flocculation-sedimentation is pellet softening. At the core of this technology is a column type reactor filled with fine sand. In this process, the water is fed through the column filled with sand at fairly high up-flow velocities, normally ranging between 60 and 100 meter/hour, creating a fluidized bed reactor operation. Caustic soda is added (and rapidly mixed) at the bottom of the column in order to almost instantaneously elevate the pH of the water to $\sim$8.5, causing crystallization of the calcium (and magnesium) in the form of calcium carbonate (calcite) onto the sand, making the grains grow into pellets of about 1 mm, which is when they become obviously heavier, are less efficiently fluidized and subsequently removed and substituted with fresh sand. Note that the softened water often requires re-carbonation in order to restore the total carbonate concentration as well as to lower the pH.

3.4.3 Ion exchange

During drinking water treatment ion-exchange resins are primarily used for water softening (i.e., removal of calcium and magnesium and enhanced removal of organic matter to reduce disinfection by-product formation and lower their coagulant and total oxidant demand. A saline solution (i.e., normally NaCl as it is a cheap and readily available bulk product) is used to regenerate the resins and produces highly concentrated brine containing the target pollutant, organic acids, sulfate, bicarbonate and chloride (McAdam & Judd, 2008).

3.4.4 Membrane filtration

Membranes are a physical barrier to remove dissolved solids and particulates. There are different classes of pressure driven membranes, classified by their pore size, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO), as described in detail elsewhere (Crittenden & Borchardt, 2012). MF and UF are typically used to remove pathogens and solids from their feedwater. Sometimes they also provide pre-treatment before NF or RO processes. MF and UF are generally operated in a dead-end configuration and periodic backwashing, normally every 30–60 minutes, is applied in order to minimize the build-up of particles/organics onto the membrane surface. The latter produces a residual stream containing chlorine and organics. On the other hand, RO and NF membranes, which are characterized by much smaller pore sizes, should rather be imagined as dense polymer layers with material-free void spaces in the separation layer of the thin-film composite membrane. They are often used for brackish and seawater desalination, resulting in a highly saline residual stream that is continuously produced, often referred to as the concentrate. Concentrate streams typically range from 10% to 30% for brackish and from 45% to 60% for seawater desalination of the feed volume. Those membranes also find application in water reuse to provide a barrier for viruses in addition to reducing salinity or micropollutants.

To protect the membranes from biofouling, commonly hypochlorite/chlorine or chloramines are added to the feed. Since chlorine in solution can damage the polymer membranes, sodium bisulfite is typically used to reduce chlorine in larger RO systems as it readily reacts with any residual chlorine to form sodium sulfate that ends up in the concentrate stream. Moreover, depending on the pH and hardness level of the water source used, pH correction with acids and added anti-scalants can be employed in order to maintain operation at a constant membrane pressure. Anti-scalants are a family of chemicals designed to inhibit the formation and precipitation of crystallized mineral salts that form scale. In addition, potentially added dispersants are polymers designed to inhibit the agglomeration and deposition of foulants onto the membrane surface. Foulants include inorganic metal oxides and hydroxides, polymerized silica, organic/inorganic colloids, and organic and biological matter. RO and NF membranes typically also require regular acid and base cleaning, which results in the generation of residual acidic or alkaline streams.

3.5 WHICH RESOURCES CAN BE RECOVERED?

Table 3.1 provides a summary of resources that can be recovered at drinking water treatment plants using commonly applied treatment processes. Note that a clear distinction can be made between the resources naturally present in the water sources and the resources (i.e., mostly chemicals) that are added during the treatment processes. As shown in Table 3.1, depending on the drinking water treatment process applied, there are various waste streams being produced, which are generally referred to as water treatment residuals (Cornwell & Roth, 2000). In a conventional water treatment plant as much as 3–5% of the plant influent can end up as solid, semisolid, and liquid residuals (Crittenden & Borchardt, 2012).

A schematic representation that provides a clear and holistic overview of the different material flows and their relative importance in terms of input and output is a so-called Sankey diagram (see Figure 3.3). The widths of the arrows are proportional to the mass flow of the different inputs and outputs added and produced during the production of drinking water. The example in Figure 3.3 depicts the average material flow of 20 drinking water production facilities using ground water as their source water for the year 2018 (personal communication, AquaMinerals 2018). Note that in the diagram the input in terms of assets like the distribution network are also included, often not considered in the context of recovery/recycling. The difference in input and output (i.e., output exceeds input) may be somewhat confusing but can be attributed to, for example, replacement of heavy old concrete/cast iron pipes to PVC as well as a temporary peak in final disposal of 'end-of-service life' infrastructure.

As depicted in Table 3.1, a wide variety of residuals is produced during the production of drinking water. It is important to realize that both the quantity of these residuals generated as well as the quality in terms of their purity and product strengths depends on both the treatment process applied and water source used. This is of crucial importance when trying to link the recovered resources with the market

Table 3.1 Commonly applied treatment processes during the production of drinking water using different water sources and the potential resources that can be recovered.

Treatment Process	Main Treatment Objective	Water Source	Chemicals Added During Treatment	Residual Stream	Potential Resources That can be Recovered	Load/Characteristics of the Produced Residual Stream
Aeration of ground water	Removal of ferrous iron ions	GW	N.A.	Iron sludge	Iron(hydr)oxides	Brown-red sludge, odorless Up to 90% of dry weight
Coagulation-flocculation-sedimentation	Removal of organic matter[a], pathogens,	GW, SW, SE	Aluminum sulfate	Alum sludge	Aluminum Organic acids	Grey sludge, often difficult to dewater, may smell depending on organics
	Ca, Mg and bicarbonate		Iron chloride Iron sulfate	Iron sludge	Iron, organic acids	Brown-red sludge, may smell depending on organics
			$Ca(OH)_2$ Sodium carbonate, caustic soda	Softening sludge	$CaCO_3$, $Mg(OH)_2$ Organic acids	2–5% of plant flow Natural colored (white-blonde-gray-brown) sludge or pellets; odorless
Media filtration (sand, activated carbon, anthracite)	Removal of solids post sedimentation	GW, SW	NA	Spent filter backwash	Aluminum, iron Manganese, organics Media filter itself (e.g., activated carbon)	A mix of Al, Fe, Mn, organics at mg/L levels
Low-pressure membranes (MF/UF)	Solids, pathogens	GW, SW, SE	NA	Spent filter backwash	Organic acids	Load highly depends on plant recovery; typically <5% of plant feed flow
	Chemical cleaning		Citric acid Caustic soda Chlorine	Cleaning solution		
High-pressure membranes (NF/RO)	Salts, pathogens, organics	GW, SEA, SE	Antiscalant Antifoulant Sodium bisulfite	Concentrate	Sodium bisulfate Phosphonates	Load highly depends on plant recovery; typically 10–25% of plant feed flow
	Chemical cleaning		Citric acid Caustic soda	Cleaning solution		
Ion-exchange (IEX)	Organic matter, nitrate, hardness	GW, SW	Salt, sodium-bicarbonate Caustic soda	Regenerate solution	Organic acids (humic and fulvic acids)Also (Na^+, NO_3^-, Cl^-, Ca^{2+}, Mg^{2+} and HCO_3^-)	0.05–10% of treated product flow depending on IEX system; low percentages can be achieved by the MIEX® process. A mix of NaCl, SO_4^-, HCO_3^- and humic and fulvic acids at g/L levels

GW = ground water, SW = surface water, SEA = sea water, SE = secondary effluent of waste water treatment plant, NA = not applicable.[a]Organic matter is the main cause of color and turbidity.

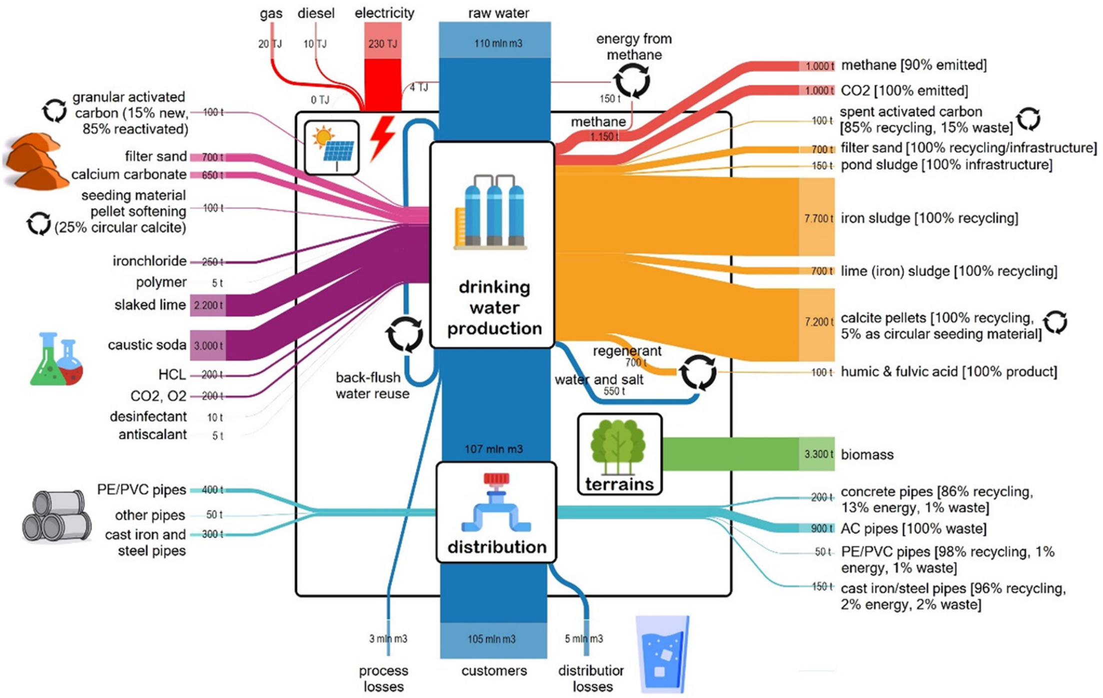

Figure 3.3 Sankey diagram of the material flows for drinking water production from ground water. The figure describes the average from 20 drinking water production facilities in the Netherlands for the year 2018 (photo courtesy: Aquaminerals).

demands and requirements. Moreover, especially in more moderate climates like part of the USA and Europe, there are also seasonal effects that affect the composition of a water source. In the warmer summer months, surface water often contains higher concentrations of natural organic matter, which results in a higher chemical coagulant dosing and thus increased sludge production. The difference in source water quality is important as there is evidently a strong correlation between the type, concentration and overall volume of residuals produced during the treatment processes and the quality of the source water. When the source water has a high load of contaminants, removing them leads in general to a larger quantity of residuals; mainly due to an increase in chemical dosing requirements to meet the required drinking water quality (i.e., drinking water production still heavily depends on the addition of chemicals). A good example to illustrate this is to compare the residual production rate using ground water and surface water as water source. The almost universal presence of suspended solids (and natural organic matter) in surface water, which is almost negligible in groundwater, induces higher coagulant dosage leading to rather large volumes of coagulation sludge. In a similar context, one could imagine that the amount of residuals produced during treatment of municipal wastewater is substantially higher due to the higher load of pollutants in the untreated sewage. Indeed, for example, for the Dutch situation, approximately 0.68 kg wet residual is generated per treated m^3 of municipal wastewater (http://statline.cbs.nl/) versus on average only 0.17 kg wet residual per m^3 drinking water produced from ground and surface water (personal communication, AquaMinerals 2018).

Regarding potential resources that can be recovered (Table 3.1), it is very important to realize that these resources often contain other impurities that in some cases need to be removed prior to beneficial reuse of the target resource. This depends on both the type and concentration of these

Table 3.2 Properties and product characteristics of resources recovered from water residuals and their potential end-use.

Residual	Color	Morphology/ Structure	Main Elemental Component	Other Substances/ Contaminants	End-use/Market Segment
Calcite pellets	White-Brown	Round pellets	$CaCO_3$	Fe, organic matter, Mn, Si	Glass, carpet, agriculture, feed, cosmetics, reuse in drinking water production, concrete (tiles), steel production
Lime sludge	White-Brown	Dewatered/ dried sludge	$CaCO_3$	Fe	Soil improvement, construction
Iron-rich sludge (produced through ground water aeration)	Brown-Red	Dewatered/ dried sludge	$Fe(OH)_3/Fe_2O_3$	Mn, As	Soil amendment, construction industry, sulfide control in sewers and digesters, constructed wetlands, P-removal surface water, As-removal drinking water
Iron-rich coagulation sludge	Brown	Dewatered/ dried sludge	Fe-complexes Organic matter Clay	Various	Soil amendment, construction industry, constructed wetlands, raw material for clay brick and cement production
Alum-rich coagulation sludge	(dark-) Grey	Dewatered/ dried sludge	Al-complexes Organic matter Clay	Various	Soil amendment, construction industry, phosphate removal, constructed wetlands cement production, alum-industry (melters)
Brine	Colorless-Yellow	Liquid	H_2OSalt	N, S	Reuse of the salt for regeneration of the resin
Humic-/ Fulvic Acids	Yellow-Black	Liquid-Powder	C-complexes	Salt	Biostimulant for crop growth, additive in feed

Note that also the filter sand/gravel (from sand filter units) as well as activated carbon (from activated carbon filtration) can be considered resources that can be recovered once they need replacement, but they are not listed in this table.

impurities and the envisaged end-use and the targeted market segment for the recovered product. Table 3.2 provides a summary of some existing end-use routes for recovery and reuse of water treatment residuals implemented by the water industry at full scale.

3.6 CHAPTER SUMMARY

In this chapter, we have discussed the major water sources used for the production of drinking water, namely, surface water, ground water, seawater and reclaimed effluent from wastewater treatment plants. The most common water purification methods currently implemented by the water industry have also been described. Furthermore, we have explained the different resources that are naturally present in these water sources themselves as well as resources that are present in the water treatment, residuals added during drinking water production and how and in which form (and concentration) these resources can be recovered. Lastly, the properties and product characteristics of resources recovered from water residuals and their potential end-use in different market segments have been described. Finally, we have also highlighted the importance of the volumes, concentrations and presence of other compounds/contaminants of the recovered resources on the resource recovery and valorization potential in various industry sectors.

3.7 EXERCISES

Exercise 3.1: In the Netherlands, some 0.17 ton (wet) residual per mega liter (ML) drinking water produced is generated. Calculate the amount of residuals produced per year in the Netherlands assuming a water usage per capita per day of 130 liters.

Exercise 3.2: Use the same residual production rate as in Exercise 3.1, but now calculate for the total amount of residuals produced on a yearly basis for the USA. Note that the average water consumption in the USA is over 400 liters per capita per day.

Exercise 3.3: Assuming an average coagulant dosing of either aluminum sulfate or iron chloride, what would the yearly production of coagulation sludge (in dry matter) be for the Netherlands, Australia, USA, India and China?

Exercise 3.4: Assuming an average coagulant dosing of either aluminum sulfate or iron chloride (i.e., $Al_2(SO_4)_3 \cdot 14H_2O$ and $FeCl_3 \cdot 6H_2O$), what would the yearly production of coagulation sludge similarly to Exercise 3.3 (in dry matter) be for two typical water treatment plant (WTP), for example 30 000 m^3/day (small to medium city) and 300 000 m^3/day (typical large plant).

Exercise 3.5: What are the key resources that can be recovered at drinking water treatment plants that are either naturally present in the various sources (i.e., ground water, surface and sea water) used for the production of drinking water as well as the resourced added to the drinking water production process? More specifically, what are the major resources that can be recovered from the following processes?

(a) Aeration of ground water;
(b) Coagulation-flocculation-sedimentation;
(c) Low-pressure membrane filtration;
(d) High-pressure membrane filtration;
(e) Ion-exchange.

Exercise 3.6: What are the most critical impurities in relation to the major resources that can be recovered identified in Exercise 3.4.?

Exercise 3.7: Provide a qualitative overview of the major resources identified in Exercise 3.4 that can be recovered from:

(a) Aeration of ground water;
(b) Coagulation-flocculation-sedimentation;
(c) Low-pressure membrane filtration;
(d) High-pressure membrane filtration;
(e) Ion-exchange.

Exercise 3.8: As discussed in this chapter, there is a clear distinction between the resources naturally present in the water sources and the resources added during the treatment processes. Design a scheme that provides an overview of resources added in the treatment processes and naturally present in different water sources used.

Exercise 3.9: A clay brick manufacturer produces 25 million bricks per year, each of them weighing about 2 kg. The manufacturer uses 10% m/m coagulation sludge from drinking water production in the brick production process. Let us assume that an average drinking water production site produces 7500 tonnes of sludge with a dry weight of 33.3% annually. How many drinking water production locations need to work together to meet the demands of this manufacturer?

3.8 DISCUSSION QUESTIONS

Question 3.1 (*drivers and market analysis*): A city of 500 000 inhabitants is evaluating the feasibility of providing iron-rich coagulation sludge from the its drinking water treatment plant for phosphate removal to its wastewater treatment plant. The WWTP currently uses iron chloride for the removal of phosphate. What data or information do you need as a basis for the feasibility analysis? What are the key criteria that could favour the use of coagulation sludge? What are the criteria that could favor the use of iron chloride coagulant?

Question 3.2 (*regulations, health protection and economic viability*): A progressive city council has firmly anchored its ambition to implement 'circular economy' by the year 2030. It is considering to apply alum-rich drinking water sludge as a soil amendment in its various parks and green areas. Its current practice is landfilling these materials as there is no clear interest from local industry to reuse this material and because of the uncertainty of the long-term impact on the soil quality (i.e. the soils are quite acidic and as such there is a potential for leaching of alum in the surrounding aquifers). You are asked to give a presentation in which you evaluate the risks and opportunities of using alum-rich sludge as soil amendment by the city council.

Question 3.3 (*technology, economy*): As the innovation manager of a large water utility, you are in charge of reorganizing the existing water infrastructure from its current situation to a more circular approach within a timeframe of 15 years. The current drinking water treatment infrastructure comprises two very large-scale drinking water treatment plants, with a capacity of 200 000 and 120 000 m^3/day for a total of 1 300 000 million inhabitants and local industry, both of which are using conventional coagulation-flocculation, sedimentation, filtration, and disinfection treatment processes. In addition, it comprises about 50 smaller drinking water treatment plants with a total capacity that equals that of the two very large-scale treatment plants. You are asked to give a presentation to the board of directors in which you evaluate the current status and justify your masterplan. Where would you focus on in terms of choice of resources to recover, location, and market segments/ end-uses? What are your key considerations/motivations?

Question 3.4 (*technology, economy*): As discussed in this chapter, in general, centralized water treatment using large drinking water production facilities is prevalent in major urban areas. Discuss the implications of this in terms of the economic potential of recovery of resources with subsequent market uptake and replication. What are the most critical non-technological aspects in order to make a successful link with the market?

Question 3.5 (*overall sustainability, social considerations*): Discuss the relative importance and impact of non-technological aspects in order to transform our drinking water infrastructure and overall management strategy as such that it perfectly fits within the circular economy. In the same context, discuss the importance of human behavior in relation to achieving sustainable water management in the 21st century, for example not using a resource may be even better than recovering resources. How can global change and resource scarcity drive the implementation of the circular economy?

Question 3.6 (*economy, product quality and volumes*): As discussed in this chapter, there are various sources for the production of drinking water including surface waters (i.e. rivers, lakes, and the sea), ground water and spring water. Which of these sources will, according to you, provide the best resources to recycle. In your answer discuss the purity of the recovered resources, economy of scale and total volumes.

Question 3.7 (*technology, regulation and social considerations*): Discuss the similarities and differences between resources that can be recovered from drinking water treatment plants and municipal wastewater treatment plants. In your answer, discuss the following aspects: (semi-)public owned, mid-to long term planning, quality and quantity, public perception and hygiene.

Question 3.8 (*supply chain considerations and robustness*): The supply chain of resources recovery from drinking water production is considered to be stable and reliable in cases where the transport/delivery of these resource is undisrupted and reliable to the end-user or processor over a prolonged period of time. However, in practice situations can take place that cause disruption to the supply chain. Discuss and analyze the following situations/scenarios: (i) failure or maintenance at the production site, (ii) change of treatment steps changing the volume and/or quality of the residual, (iii) scaling the production up or down (e.g. during a dry season or when (dis-)connecting a neighborhood or changing the source of the water.

Question 3.9 (*supply chain considerations, circular resources and end-user*): Calcite can be recovered during drinking water production in cases where a softening step is required. Calcite can be ground, sieved and sterilized and can be re-used within the treatment process as seeding material, calcinated calcite can be use as new quicklime for the softening process. Discuss the terms supply chain considerations, end-user and process stability in relation to the benefits of reusing the calcite.

Question 3.10 (*product quality, impurities end-user*): A benefit of using ion-exchange resins for the removal of natural organic matter (NOM) is that upon regeneration of the ion-exchange resins, a concentrated NOM solution is generated that can be beneficially used as a biostimulant in agricultural applications for plant growth promotion. Discuss the terms supply chain considerations, end-user and product quality in relation to the economic benefits and practical feasibility. With respect to the product quality, in particular discuss the potential implications of the fact that regeneration of the ion-exchange resins is typically achieved by using a concentrated salt solution.

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