

## Chapter 12

# Closing the loop within the water sector: circular resources

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### 12.1 INTRODUCTION

A crucial difference between more conventional treatment methods that are based around dissipative pathways that makes hazardous things ‘disappear’ and resource recovery from used water is the need to ‘do something’ with the resources that are recovered. This implies that the role of utilities goes beyond that of the traditional engineering practice and (waste)water management and regulatory compliance. Provided that the water company wants to make this transition to a more circular arrangement of its processes, it also needs to include non-engineering considerations like social acceptance of the recovered resources, commercialization and marketing, cross-sectional collaboration with potential end-users in market segments and industries outside that of the water industry. The latter will most likely have important complications for management practice and required skills in the situation where resource recovery from water will become the central theme within our urban water management infrastructure. One can appreciate though that, ultimately, the most critical aspect in order for resource recovery from used water to become a central element of our urban water infrastructure in the 21st century and a driving force within the circular economy, finding an end-user that is satisfied with: (i) the quantity of the recovered materials; (ii) quality of the recovered materials; and (iii) robustness and reliability of the supply chain of the recovered materials.

There are several important aspects in relation to the quantity of the recovered materials to consider. First, what is the volume of the recovered resources/materials versus the end-user requirements? By definition there will be an imbalance between supply and demand. This imbalance is primary the challenge for the supplier to overcome, not the end-user. Second, what is the overall market size of the recovered resources/materials? Is the recovered material considered a useful resource or a replacement of a raw material for the production of other products? Third, how constant is the volume/amount of the materials that can be recovered? Is there, for instance, seasonal influence or weekend/weekday difference? There are also several important aspects in relation to the quality of the

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recovered materials. First, what is the achievable quality of the recovery materials compared with the quality of alternative resources and/or raw materials? End-users will only pay a premium prize when the quality of the recovered materials is equal to or exceeds that of the currently used resources and/or other available alternatives. Second, what is the reliability in terms of the quality of the recovered material? In other words, does the recovery process allow for the production of an end-product with a constant quality? Lastly, in addition to the quantity and quality, a critical aspect is the robustness and reliability of the supply chain of the recovered materials. Can a constant supply of recovered materials be guaranteed at all times?

One can imagine that the above-described characteristics could be seen as possible constraints and/or reluctance from potential end-users outside of the water industry. The latter is especially the case when the recovered materials are of low cost/value (in comparison with the overall cost of the production process of the end-user) or, for example, in situations where the recovered material is considered a bulk product that is required in large quantities. Indeed, this is often the case, for instance for recovered sand (see Chapter 1 for more details). This is a widely available bulk product with a low intrinsic value. There is no sense of scarcity for this material and possible customers have the choice between a fairly large number of potential suppliers of 'recovered sand'. The construction and demolition industry has, for instance, a large demand and supply volume, respectively, in recovered sand.

Let us imagine a situation in which one would be the person that is responsible for the process for recovery of the resources and moreover is also the person that is the end-user of the recovered materials, that is being your own customer? In other words, are there situations in which the recovered substances can be used in the same process? This could potentially substantially simplify the situation. This is in fact not fiction at all; there are various real life proven and established methods that have been implemented by the water industry. The latter has – apart from the expected positive environmental impacts (see Chapter 22) – two major advantages. First, the sector is its own customer and that saves a lot of uncertainties concerning the marketing of the recovered materials/resources. Experience has learned that the latter can really accelerate projects, investments, market uptake and replication (personal communication with representatives of the water industry). Second, it forces the water sector to think as a customer of their own materials. Being both the supplier and customer at the same time creates the notion and emphasizes on the importance of the product quality, quantity and the reliability/security of the supply-chain within the organization itself.

## 12.2 LEARNING OBJECTIVES

This chapter aims to define important concepts in relation to circular resources like 'cradle-to-cradle', waste management hierarchy and the precautionary principle as well as put them into a historical context. The different approaches in relation to circular resources and sustainable use of resources are also explained. This chapter will also describe and discuss the (circular) resources within the water sector and the role the water sector can play in becoming (more) circular. Lastly, various real-life full-scale examples of (recently developed) circular chains within the water sector are provided. By discussing these topics, at the completion of this chapter you should be able to:

- Define the concepts of 'cradle-to-cradle', circular resources and the Waste Management Hierarchy in your own words.
- Understand the difference between linear and circular processes.
- Understand the complications of embedding resource recovery as the central theme in urban water management on the key roles/task of water utilities.
- Explain the different approaches as it comes to sustainable use of resources.
- Explain the role the water sector can play in the transition to a more circular economy.
- Give examples of circular (re-)sources in the water sector.

## 12.3 CIRCULAR RESOURCES: HISTORICAL CONTEXT, CONCEPTS, AND PRINCIPLES

### 12.3.1 Historical background – the creation of a consumption society with linear use of resources

After World War II, economies over the world started to flourish. This looks like a long time ago, but in terms of sustainability this is actually not that long ago at all. This can be explained by the most commonly used definition of sustainability:

‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’. [1]

The word future generation refers to the need for long-term thinking, that is thousands and thousands of years. In this context, one can appreciate that a timeframe of only some 75 years is not that long at all. One of the pillars under this economic growth was ‘consumption and linear use of resources’. Consumption was stimulated by a hefty increase in production volume and decreasing production costs. The relatively low consumption prices led to a less frugal use of products, products that were also less durable than those produced before this era. This altogether led to an exponential growth in volumes of waste and wastewater. In Europe this led for instance to an increase from 100 kg waste per capita per year in the early 1950s to over 480 kg waste per capita per year by the year 2016 (<http://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20180123-1>).

This increase in waste volumes was at first managed by the local municipalities. They organized waste collection and the dumping of the wastes in local landfills. This worked (and in some regions still works) for quite some time, but continued flow towards these landfills led to capacity problems. Research furthermore showed problems with the leaching of hazardous components to, for example, groundwater, often due to illegal dumping of wastes or even ignorance. In the early 1970s realization kicked in that this ‘single use and throw-away’ society could not last forever. For example, The Club of Rome published a very influential report entitled ‘The Limits to Growth’ (<https://www.clubofrome.org/>) [2]. This report described the use of computer simulations to prove that economic growth cannot continue forever due to the depletion of resources, and would ultimately result in the collapse of our society by the end of the 21st century. The first oil-crisis in the early 1970s further strengthened public concern about future resource scarcity and the overall sustainability of our society. Despite this increasing and more widespread concern and environmental awareness in the following decade(s), not that much changed in terms in terms of resource efficiency in the decades ahead; which was also the case for the water industry.

### 12.3.2 Concepts and principles

#### 12.3.2.1 *The waste management hierarchy*

By the end of the 1970s it became evident that with an ever growing population, accompanied with increasing amounts of waste being produced, a paradigm shift was needed in order to deal with this enormous challenge our ‘consumption society with linear use of resources’ had created. This realization asked for new (decision) models in order to understand what is preferred in terms of sustainable use of resources. The most well-known model globally is known as ‘the waste hierarchy’, which is depicted in [Table 12.1](#). It became a popular tool that evaluates different processes/options in order to select the most favourable in terms of sustainability. Since its conception in the early 1970s (e.g., the waste management hierarchy was embedded for the first time into European waste policy in 1975; Waste Framework Directive (1975/442/EEC)), the waste hierarchy has become one of the key pillars of environmental regulation that has been embedded in various national regulatory principles and guidelines as well international treaties and covenants.

The list provided in [Table 12.1](#) gives a good comparison of the different routes and their hierarchy in terms of preference. However, while it is considered a very useful concept and embedded in various policies, the table also highlights the simplicity of the concept in the sense that several important

**Table 12.1** The waste management hierarchy.**Waste Hierarchy – Most Favourable Solutions (from most to Least Favourable)**


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1	<i>Quantitative prevention/Refuse</i> Avoid the use of a product or material
2	<i>Intensify use/Rethink</i> Use a product much more intense, for instance (1) using a MRI in an hospital 24/7 instead of the normal opening hours or (2) sharing products
3	<i>Qualitative prevention/Reduce</i> Use other or less materials giving a lower impact in the use, but also choosing those that give a lower impact in the waste phase
4	<i>Product re-use</i> Re-use a product elsewhere in its original function
5	<i>Repair/Refurbish</i> Repair a product so it can be used in its original function or restore old products and bring up to date
6	<i>Re-use parts/Remanufacture</i> Re-use parts of a disposed product in its original function
7	<i>Recycle parts/Repurpose</i> Recycle parts of a product in another function than its original
8	<i>Material recycling</i> Process materials to obtain new materials that can be used in its original or new function
9	<i>Use as fuel/Recover</i> Incineration of materials with energy recovery
10	<i>Incineration as disposal route with material recovery</i> Incineration with no/minor energy recovery but with recovery of (some) materials
11	<i>Incineration as disposal route without material recovery</i> Incineration with the sole goal to destroy the waste and/or reduce the volume
12	<i>Landfilling</i> Dumping in landfills

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aspects are not included/discussed, such as various economical, technical, and environmental considerations that ultimately can result in a different waste management strategy adopted in practice. This is for example the case when:

- (1) A more desired route is much more expensive than the less desired one. For instance, repairing is more expensive in labour costs than re-use parts of the product;
- (2) Reusing a product is not possible in terms of the specs on hygiene and human health. For instance, the food/beverage and medical industry have evidently very high standards with respect to human health and hygiene, making re-use in some cases almost impossible;
- (3) The environmental impact of a more desired route is negative (or less positive). This may be the case in situations where the materials are regenerated (material recycling) and this regeneration process consumes, for example, a lot of energy, water or chemicals.

Another important aspect, besides the multiple ways of looking at the use and pathways of resources and materials in the water sector by means of the waste management hierarchy, is what the terms and definitions used in describing them (e.g., re-use, recycle and recover) really stand for. For instance, the terms 're-use' and 'recycling' are often used to describe the 'good use' of a residual, but both terms in reality mean something completely different. Recycling refers to the process of converting waste into new materials, while re-use refers to the re-use of a material in its original function. It is therefore important to get a fundamental understanding and detailed knowledge of what these different terms

really comprise. In a practical situation, it is therefore strongly advised to inquire with the client, regulator or costumer, to what they are referring to in terms of 'recycling', 're-use', 'recover' of the materials' in order to avoid any confusion and/or misunderstanding.

Various countries have adapted the waste management hierarchy in their waste-policies. As mentioned above, the European Union incorporated this waste hierarchy already in 1975 in the Waste Framework Directive (1975/442/EEC) and has after that revised its legislation on this issue several times (e.g., 1989, 1996 and 2008). Governments have, by means of implementing the Directive into national regulations, eminently the ability to influence the 'pathways' of materials/resources. Indeed, an expression often used is 'regulation and policies drive innovation'. The importance and impact of regulation/policy on practical and economic feasibility of resource recovery cannot be emphasised enough (see also Chapters 13–15). Examples of direct influence of regulation include (but are not limited to):

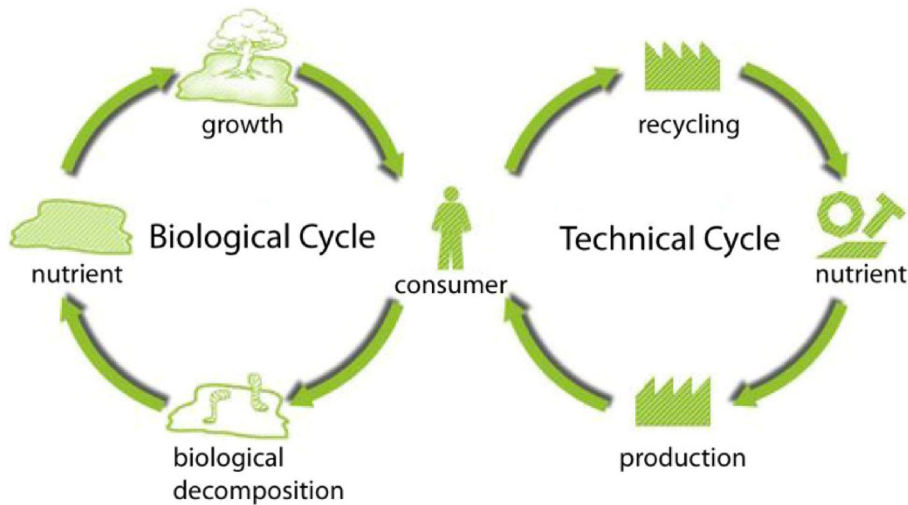
- (1) *Stimulate desired routes by implementing subsidies* – In order to stimulate innovation and desired resource management approaches one can provide subsidies on innovation or create taxation benefits;
- (2) *Discourage undesired routes by means of taxation* – With this type of taxation, the overall economics of alternative routes that are considered more environmentally friendly and sustainable (i.e., thus higher up the waste hierarchy chain), become more attractive from financial point of view. Examples of this form of taxation include for example taxation on landfilling (i.e., landfill levy) and incineration;
- (3) *Prohibit undesired routes* – This can be regarded as the most powerful and direct influence of regulation on resource management. A good example for instance is the prohibition of landfilling of recyclable/reusable materials.

### 12.3.2.2 The 'cradle-to-cradle' concept

The phrase *cradle-to-cradle* was already introduced in the 1970s by Walter R. Stahel, but has become very popular since the publication of the book entitled 'Remaking the way we make things: Cradle to cradle' by William McDonough and Michael Braungart in 2002 [3]. The basis of the cradle-to-cradle philosophy is that processes, materials and products are designed in such a way that after their service life these materials can be used again. The basis also lies in a well thought out design of the processes where these residuals emerge. These processes are designed in such a way that the emerging residuals 'fit' a next destination or use. In the case of the urban water management, by-products are produced, and waste streams arise. So, with the ambition to 'adapt and transform' these materials into circular resources that can be completely incorporated into the cradle-to-cradle philosophy, it may thus have (substantial) complications for the design and (waste)water treatment processes. Indeed, one can appreciate that design criteria need to be extended beyond the efficiency, robustness and cost-effectiveness of the treatment process alone. Knowing and understanding what the exact specifications of these circular chains will need to look like is evidently of crucial importance in order to make this 'design' fit.

The *cradle-to-cradle* philosophy distinguishes two routes, namely, the biological cycle and the technical cycle (see Figure 12.1). It is of great importance that both cycles remain in a healthy and valuable state. This means that they these cycles remain physically apart and do not interfere with each other. Hybrid materials (materials consisting of various different elements) lead by definition to problems in the recycling phase.

The biological cycle is meant for materials that are biodegradable, thus materials that can be completely decomposed through biological processes such as composting, digestion and fermentation. The degraded materials can be used as 'food' for the soil and the crops that grow on it. For this cycle it is important to take into account the organic balance in the soil. The quantity of organic material added to the soil must ideally be in balance with the quantity that is removed in the form of crops (or other plant-based products such as timber) or lost by erosion or degradation.



**Figure 12.1** The biological and technological cycle within the cradle-to-cradle philosophy [3].

The technical cycle contains non-biological materials such as metals, sand and plastics. These materials keep circulating as valuable resources for the industry. The great challenge in this cycle is to maintain as consistent a level of quality as possible during and after use. When the quality cannot be maintained at a desirable level, reusing or recycling may not be possible anymore. In these situations, the material needs to be down-cycled to a 'lower end' product or application, or even worse, disposed of or destroyed. A frequently used term is the so-called 'closed loop' (sometimes also referred to as a 'continuous loop'). The latter term refers to a situation in which a material used in a certain product (e.g., lamp, furniture, concrete tile, and carpets) is returned back to the original manufacturer where the material is completely re-used in the same product. This concept has gained significant interest in recent years and is growing rapidly. Producers and manufacturers in fact use this as a strong marketing-tool. There are even business-concepts where the ownership of the product remains with the producer and the customer leases or rents the product (e.g., Fair phone, Philips Lightning, Technogym). This business model is often referred to as a 'product as service model'. In order to repeatedly recycle component materials from the products that contain them, it is evidently important that these individual components can easily be recovered from the product it is used in. This asks for another way of looking at designing products: *design for disassembly*. In this cycle, materials that are considered harmful/toxic in the production, use and recycle phase should be avoided. Of course, one should always aim to avoid the use of such materials at any time, but this is of special concern within the circular economy as it makes the re-use and recycling opportunities much smaller or even impossible.

#### 12.4 CIRCULARITY WITHIN THE WATER SECTOR

When looking at the water sector one could consider three distinctive 'resource clusters' in which resources/materials can be recovered:

- (1) *The (waste)water treatment process*. This process characterises itself by the use of chemicals (e.g., coagulant, metal salts, activated carbon) and the emergence of residuals/by-products (e.g., sludge, calcite, gasses). New technology increasingly leads to more recovered substances from these sludges, like cellulose, energy and struvite.

- (2) *The (underground) distribution network.* This cluster contains mainly pipes, pumps and buffers. It is less (material) dynamic than the treatment process, but nevertheless contains a vast volume of materials. In fact, the distribution network comprises the largest fraction of the overall asset value of our urban water infrastructure;
- (3) *The water itself.* The (drinking-) water companies use sea-, surface- or groundwater for the production process. The wastewater companies treat the 'used-water' and discharge the treated water.

While the ambition of governments and the water industry to become more 'circular' is firmly anchored in various policies and guidelines, the majority of the resources used in the water sector still originate and rely upon the use of virgin materials. There are several reasons for the latter that are worth mentioning:

- (1) This choice for virgin material is often regarded as the 'safest'. Obviously, the treatment process has the highest priority and can thus not be subjected to any 'risk' of new products/materials made from non-virgin materials. However, it should be emphasised that this argument is not always valid anymore, as there are plenty of situations where the recovered materials have in fact a higher quality and spec than the virgin products/materials previously used.
- (2) Various segments of the water sector have strict requirements on the use of materials and resources in terms of hygiene. The most obvious and clear-cut example would be the production of drinking water. The requirements for the chemicals used in this process (e.g., for softening or coagulation) are more difficult for non-virgin than virgin products/materials to meet, but also here recent innovations lead to new opportunities.
- (3) There is often no clear incentive and/or drivers to change to different materials are lacking. So why take the risk when the current materials have proven to work just fine.
- (4) There is a lack of clear guidelines and regulation on the use of resources recovered from water (see Chapter 19 for more detail).

The improvement of a more circular use of materials in the water sector can be found in the re-use/recycling of the discarded materials from the treatment process or distribution network. Most of these materials are currently landfilled, incinerated or find their way into backfills. Surprisingly, in many cases, water companies do not even know where these materials ultimately end up (personal communication water utilities and companies). However, with some extra attention to, for instance, the quality, volume, possible consumer of these materials and better management of the materials, a better use of these residuals is within reach, for example: (i) valuable materials can be recovered after incineration, such as P-recovery from the ashes of sludge incineration; (ii) residuals can be processed and recycled, such as the use of municipal wastewater sludge in agriculture or (iron-) sludge for the production of clay bricks; (iii) products such as pumps can be repaired; (iv) water can be re-used in the various processes; and (v) a better use of materials may lead to less use and therefore prevention.

However, in the above-mentioned five examples beneficial use of residuals is not 100% circular; these materials are used in processes/applications not within the water sector itself. From a more holistic point of view, the ultimate goal in the cradle-to-cradle principle would entail that resources are recovered and re-used within the water sector. Indeed, this is certainly something the water sector should pursue; would it not be great when the water sector becomes completely resource independent and self-sufficient? That is more difficult than it appears at first sight. After all, it is not only the challenge to make the water circular again, but what about the (underground) infrastructure, as well as chemicals and energy needed for the treatment processes and the residuals coming from the treatment process itself? Operating circular means also making these resources circular. Obviously, it will be very difficult for the water sector to completely achieve this goal. Nevertheless, a lot of progress can be made, and in fact there are quite a lot of examples of circular resources within the water sector, some of which are discussed in detail in the following section.

### 12.4.1 Circular resources within the water sector: real-life case studies

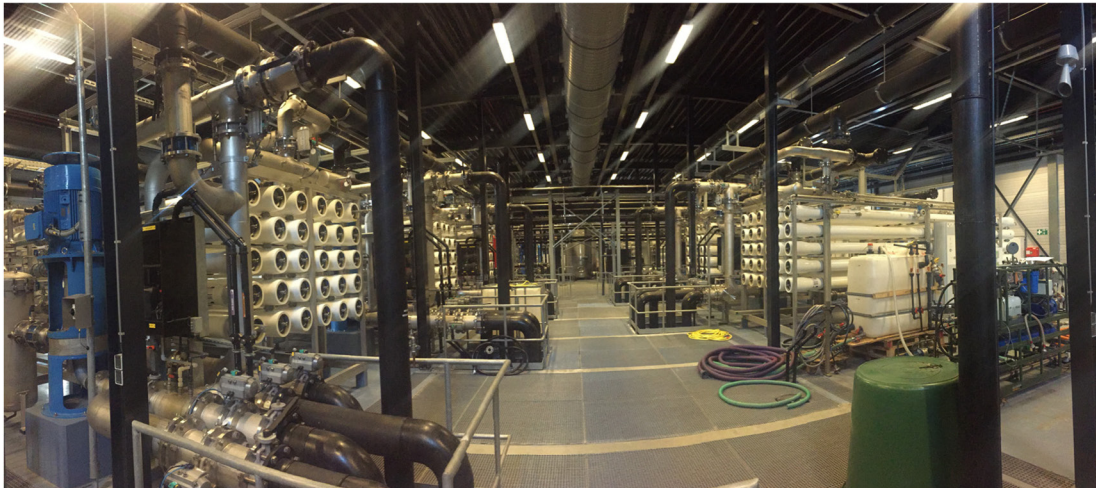
As discussed above (and in various other chapters of this book), there are various examples of resources and materials that can be re-used within the water sector. In this paragraph, we will describe four ‘circular resources’ within the water sector in more detail by discussing four real-life case studies within different segments of the water sector, that is drinking water production, food and beverage industry, and municipal wastewater treatment.

#### 12.4.1.1 Case study 1. Water re-use: the Ultra-Pure Water Factory Emmen

A good example for a Water Re-use Case study is the Ultra-Pure (UPW) Water Factory Emmen ([Figure 12.2](#)), The Netherlands. This wastewater re-use plant has been in operation since early 2010 and upcycles the effluent from the wastewater treatment plant of the city of Emmen into ultra-pure water



(b)



**Figure 12.2** (a) Ultra Pure Water Factory Emmen (front) with WWTP Emmen (background); (b) Interior of the UPW Factory Emmen with RO membrane unit in front (photo credits: Arjen van Nieuwenhuijzen, Witteveen+Bos).



to be used by Shell-NAM for oil extraction. The output can be as much as 10 ML/day. Shell-NAM converts the UPW into steam, which is injected into the Schoonebeek oil fields to render the thick, viscous oil more fluid. It has been estimated that by 2036 120 million barrels will be extracted using this technique.

Wastewater and industrial water process technologists and specialised engineers from Water Company Drenthe, Waterboard Velt and Vecht, WLN and Witteveen+Bos consulting engineers developed, investigated and designed the individual technologies and the complete integrated processes design. The purification process has been positively assessed by external, internationally recognised engineers and water professionals.

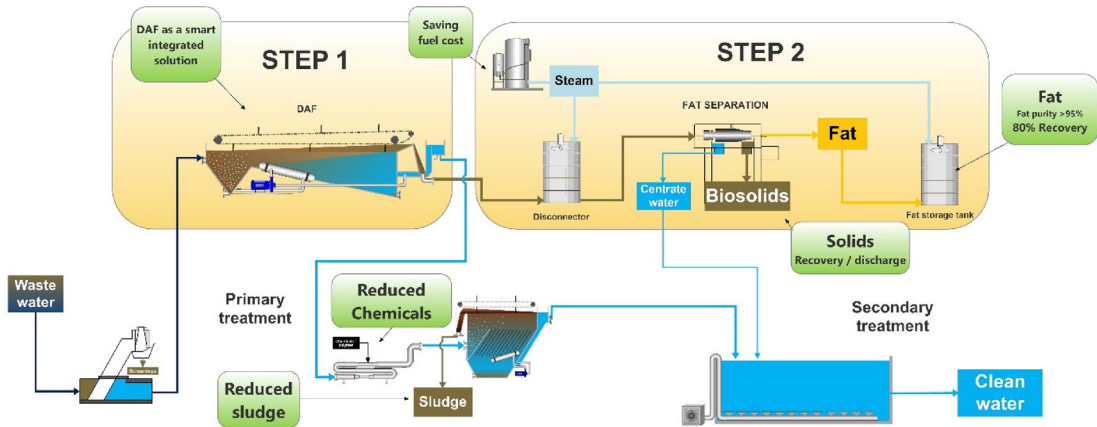
One can imagine that in order to produce the ultra-pure water from raw domestic wastewater requires a smart combination of various treatment methods. In fact, the innovative combination of treatment techniques utilised in the UPW Factory is unique, consisting of existing and innovative techniques comprising a sequence of five treatment and upcycling steps using the effluent of the WWTP as influent (more information on the process configuration can be found elsewhere; <https://nwtr.nl/en/puurwaterfabriek.php>):

- (1) *Pretreatment* – Rotary screens remove the larger impurities and objects, such as leaves and hairs. A brushing mechanism ensures the screens are automatically kept clean and clear. The filtered waste together with the rinse water is collected in a buffer, from where it is returned to the wastewater treatment plant.
- (2) *Ultra-filtration* – Submerged UF membranes remove the insoluble substances from the WWTP-effluent. The water is vacuum pumped from the basin through the walls of the straws. Any waste is caught by the exterior walls of these membrane straws. The wash water is returned to the Emmen WWTP. The clean water is then passed to the next step of the purification process.
- (3) *Biological activated carbon filtration* – The BACF is required to prevent and control bio-fouling of the reversed osmosis membranes. By adding pure oxygen, a favourable environment for bacteria is created in the activated carbon filter, which convert organic material into water and carbon dioxide, thereby considerably reducing bio-fouling in the RO membranes. The rinse water and the biomass are returned to the WWTP. At this stage the water is almost of potable quality.
- (4) *Reversed osmosis* – The RO membrane installations remove any minerals and left over impurities. The total installed RO membrane surface is 40,000 m<sup>2</sup>. During treatment, approximately 20% of feed water is concentrated and returned to the WWTP. Adding anti-scaling prevents fouling of the membranes. Reverse osmosis happens in two stages; both installations are connected in a circuit.
- (5) *Electro deionisation* – Removal of any remaining minerals (ions) takes place with the electro deionisation unit. This step is a relatively new development in the field of water purification: a combination of membrane filtration and ion exchange. After EDI the produced water is specified as Ultra Pure Water and feeds the steam production facilities of Shell-NAM. The UPW factory is the world's largest EDI (electro deionisation) facility currently in operation.

Noteworthy to mention is that also parts of the UPW Factory itself were based upon the 'cradle-to-cradle' concept, that is the concrete floor was poured using a mix which included crushed concrete from demolished structures.

#### **12.4.1.2 Case study 2. Recovery and on-site re-use of fat as an energy source in the food and beverage industry**

Many industrial wastewaters in the food and beverage industry including meat processing, candy and palm oil contain relatively high concentrations of fat. This fat can be effectively recovered using a combination of physical chemical separation techniques, as depicted in [Figure 12.3](#).



**Figure 12.3** Schematic representation of the overall wastewater treatment process with Nijhuis AECO-FAT for the efficient recovery of fat in two steps.

This process has been realised for one of the leading bacon processing factories in Ireland to turn their flotation fat into recovered resource (Figure 12.4). The factory of 10,500 m<sup>2</sup> operates six bacon lines with a total capacity to process (i.e., slice, cook and freeze 85,000 rashers (thin slices of bacon) per hour. The latter is equal to a weekly production of about 200 tonnes of cooked strips. This production process comes with the production of substantial amount of wastewater with an average flow of 600 m<sup>3</sup> wastewater per day that is associated with high COD concentrations on the order of 30,000 mg/L and an oil and grease concentration of ~500 mg/L.

The fat recovery process can be divided into two main steps, namely: (i) fat removal; and (ii) fat separation and re-use. In the first step, the wastewater is treated by dissolved air flotation (DAF) to remove fat and solids. In general, a removal efficiency of 45–70% total suspended solids (TSS) and 50–80% oil and grease is achieved. The produced sludge is a mixture of water, fat and solids in ratios depending on the wastewater origin and recovery method implemented. In the bacon processing wastewater more than 25% of the sludge is fat, while for instance poultry slaughterhouse wastewater sludge typically contains around 90% water and 7% fat.

The wastewater leaving the DAF is subsequently treated in a second DAF unit in combination with enhanced chemical flocculation and coagulation to remove residual solids which are not removed in the first DAF unit. This second DAF is followed by a secondary aerobic biological treatment step prior to discharge onto surface water or sewage. During the second step of the AECO-FAT system, the produced sludge is heated in a disconnecter before entering the solid separation stage. In the latter, the sludge is separated into a liquid fat, a water and a solids fraction. The recovered fat is stored in heated tanks to keep it liquid for transport. The centrate water from this second step is treated in the biological reactor (see Figure 12.3). The first step of the AECO-FAT system in Ireland produces a maximum of 30 m<sup>3</sup> sludge per day. Around 6 m<sup>3</sup> of pure fat is recovered from this sludge per day. Generally, more than 80% of the fat present in the flotation sludge will be recovered. The specific recovery is dependent on the composition in the sludge (e.g., fat content, physical structure/properties etc.) which in turn depends on the wastewater origin.

In this project, daily 3 m<sup>3</sup> fat is used to feed a steam boiler and supply the entire factory with energy in order to become completely energy self-sufficient. The quality of the produced fat in this case is also suitable for biofuel production and the residual 3 m<sup>3</sup> fat per day is sold for this purpose. This 6 m<sup>3</sup> daily recovered fat has an energy content of 209 GJ (assuming that fat has an energy content of 40 MJ/kg and a density of 870 g/L) which is equivalent to about 58 MWh or 5500 L of diesel (assuming the energy



**Figure 12.4** The case study plant overview (left top), the dissolved air flotation with 'fat' flotation sludge (right top) and the recovered fat (bottom).

content of diesel is 45.3 MJ/kg and the density of diesel is 840 g/L). In addition to becoming energy self-sufficient, the above-described fat recovery and re-use process also comes with additional benefits including a reduced chemical footprint and lower sludge production. The reduction in chemical use is due to the fact that the first DAF unit produces sludge *without* the addition of chemicals (note that chemicals cannot be used otherwise the fat could not be used in the boilers), which lowers the chemical requirement for the second DAF by ~50%. Moreover, the total amount of sludge to be disposed is decreased as fat is removed from the sludge and is no longer disposed with the sludge. The revenue of fat and the cost reduction of both chemicals and sludge discharge are depending on the local costs for the chemicals, sludge discharge and the energy price or price for which the recovered fat can be sold. It is the combination of these benefits of fat recovery that makes its business case. This makes it a recovery solution which is applicable around the globe for wastewaters containing high concentrations of fat such as wastewaters of slaughterhouses, protein processing plants (including bacon) and confectionary plants.

#### 12.4.1.3 Case study 3. Re-use of chemical coagulants

Chemical coagulants play an important role and are dosed in enormous amounts at various places in our urban water management. They are dosed for: (i) the removal of turbidity, colour, natural organic



**Figure 12.5** Application of iron-rich drinking water sludge as a means to minimise eutrophication in lakes (photo credits: Olaf van der Kolk, Aquaminerals).

matter (NOM) and pathogens during drinking water production; (ii) corrosion and odour control in sewage distribution systems; and (iii) phosphorus removal and sulphide control during anaerobic digestion at wastewater treatment plants (WWTPs). By far, aluminium sulphate (also known as alum) and iron salts (both ferrous and ferric chloride) are the most commonly used chemicals. On average, the iron content (expressed as elementary Fe) is about  $27 \pm 15\%$  (personal data AquaMinerals of nine drinking water treatment plants with data gathered over a period of 10 years). With respect to beneficial re-use of these chemicals, especially iron-based coagulants are of interest as iron possesses the ability to remove both hydrogen sulphide and phosphate. Obviously, the iron content differs from one water treatment plant to another as it depends highly on the quality of the surface water. There is no need to use high-quality virgin coagulants in a sewer- or WWTP-context and the use of iron rich drinking water sludge (Figure 12.5) is a great example of circular resources in water sector and managing chemical coagulants in this way helps to close the loops within the water sector.

Another example of beneficial re-use of iron is the use of iron rich ground water sludge. A fundamental difference is that in this example the iron is not added to the water as a chemical coagulant, but naturally present in the ground water in dissolved form as ferrous iron ( $\text{Fe}^{2+}$ ). In this situation, it is in fact considered a pollutant that needs to be removed from the water in order to meet drinking water regulations. The latter is normally achieved by means of aeration, thereby oxidising the ferrous iron to ferric iron ( $\text{Fe}^{3+}$ ), which is non-soluble at circumneutral pH values. This process leads to a sludge which contains (very) high levels of iron (hydr-)oxide (i.e., as high as  $>80\% \text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$  on a dry matter basis). On average, the iron content (expressed as elementary Fe) is about  $34 \pm 11\%$  (personal data AquaMinerals of 87 drinking water treatment plants with data gathered over a period of 10



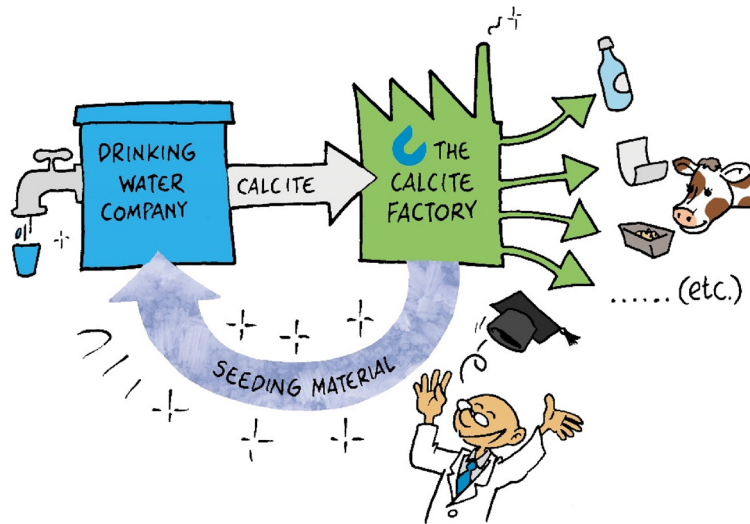
**Figure 12.6** Iron oxide pellets produced from iron-rich ground water sludge (photo credits: Olaf van der Kolk, AquaMinerals).

years) and can therefore be considered an excellent ‘low-grade’ alternative to virgin iron chloride for sewer corrosion and odour control. Since iron (hydr)-oxide is a very reactive material, this sludge is not only used in sewers for sulphide control, but for instance is also used in digesters, simply by adding it as a slurry to the anaerobic digester. Indeed, several utilities have implemented this approach with excellent results. Examples of wastewater utilities that are using iron rich drinking water sludge for sulphide control in sewer network are Hamburg Wasser, the combined drinking- and municipal waste water utility of the city of Hamburg (Germany) and the wastewater utilities Drents Overijsselse Delta and Waterschapsbedrijf Limburg (the Netherlands). Another application is the use of iron-rich drinking water sludge as a low cost ‘filter’ to minimise eutrophication due to excess phosphate in lakes.

Moreover, it was found that, with some processing of this sludge, the iron can be re-used in the water sector in the form of pellets (Figure 12.6). The method of producing pellets is a rather simple process that consists of the drying of the sludge, adding an organic additive and pelletising it to a granular absorbent. These pellets can be used in treating biogas from anaerobic digesters and/or for odour control in pump pits and wet wells in sewer networks. It can also be used in removing P from surface water, especially in regions where this water contains too many nutrients, leading to algal blooms. Another option to use these pellets is to remove arsenic during the production of drinking water. A key advantage of using pellets instead of sludge is that the process is better controllable and suitable for treatment of both gases and water streams, but it also gives the user the opportunity to easily change a saturated filter with a fresh one, whereas this is not possible with sludge.

#### **12.4.1.4 Case study 4. Circular calcite**

Pellet softening is often used as a step during the production of drinking water from the removal of hardness in the form of calcium (as well as magnesium). In this process, the water is fed through a column fed with sand at an up-flow velocity of 60–100 meter/hour. This applied up-flow velocity keeps the sand in suspension. Caustic soda is added at the bottom of the column to elevate the pH of the water to  $\sim 8.5$ , causing calcium to crystalize onto the sand (which acts as a seeding material) in the form of calcium carbonate, also known as calcite. This particle starts to grow and, due to the constant shear caused by the up-flow velocity, the calcite particle is polished and rounded. When this



**Figure 12.7** Illustration of the 100% circular calcite concept.

particle reaches a diameter of approximately 1 mm, it becomes too heavy and sinks to the bottom of the reactor and is subsequently continuously removed. The sand-calcite particle residual is among others used as resource in the steel-industry, glass-industry and as lime fertiliser in agriculture [4]. A considerable limitation of this process in terms of beneficial re-use of the calcite is actually the sand. The presence of the sand is considered a nuisance for the various re-use applications mentioned above. For example, a lot of water companies use garnet sand (due to its high specific gravity), which is rich in iron. This iron is an unwanted component for the production of white (colourless) glass, garnet-containing softening pellets are therefore not fit for this type of glass. In addition, there are applications where the calcite needs to be processed by grinding, drying, sieving and sterilisation to the desired size distribution (for instance as filler in paper, plastics, feed). The sand-core is much harder than the calcite, leading to the wearing of the mill and so a significant increase in costs.

If the calcite itself could be used as seeding material, the resulting pellet would consist of 100% calcite and would therefore become a more applicable and valuable residual with several industrial applications. Therefore, an R&D project was initiated by a collective of Dutch water companies (Brabant Water, Waternet, WML and Dunea) in the year 2014. The overall aim of this project was to develop a softening method that used ‘Dutch Calcite’ as 100% circular seeding material (Figure 12.7).

This ‘Dutch Calcite’ was made from softening pellets from the water companies themselves. After intensive research by KWR (2015; <https://www.kwrwater.nl/en/actueel/high-value-re-use-of-lime-from-drinking-water-softening-is-sustainable-and-profitable/>), it was found that these residuals from softening pellets can, after being ground, sieved and sterilised, be used as new seeding material within the same process. Equally important (rather surprisingly), the softening process itself became more efficient using calcite rather than garnet sand in terms of the use of seeding material and calcium removal rates. Based on these very promising results, several drinking water companies indicated that they wanted to implement this ‘Dutch Calcite’ in their processes. Since this is a completely innovative and novel process, no infrastructure to make this product on a rather large scale was available. Therefore, the water company of Amsterdam (Waternet) and the UK-based mineral processor Advanced Minerals took the initiative to set up a processing plant in Amsterdam. It started supplying drinking water companies with seeding material at the end of 2017 (see Figure 12.8).



**Figure 12.8** (a) The calcite factory (Amsterdam, The Netherlands); (b) Beneficial re-use of 'Dutch Calcite' for the production of carpets; and (c) comparison between 'Dutch Calcite' and conventional sand-calcite pellets.

## 12.5 CHAPTER SUMMARY

In this chapter, we have discussed the following concepts: (i) consumption society (with linear use of resources); (ii) 'cradle-to-cradle'; and (iii) Waste Management Hierarchy. We have described the history and development of the circular economy throughout the last decades of the 20th century with a special focus on the main opportunities and challenges for the water industry to play an important role in the transition into a circular economy through changing from linear to circular water management practices. One of the key considerations for the water industry was found to be how to embed resource recovery as the central management theme in urban water management in the context of the traditional roles/tasks of (waste)water utilities. A crucial difference between 'water management through removal processes' versus 'water management through resource recovery' identified was the need to 'do something' with the resources that are recovered. As such, the role of utilities would need to go beyond that of traditional engineering practice and regulatory compliance. The duties/considerations of utilities would also need to include commercialisation and marketing, cross-sectional collaboration with potential end-users in market segments and industries outside that of the water industry. The latter could be avoided in situations where the water industry is its own customer; the person that is responsible for the process for recovery of the resources is also the person that is the end-user of the recovered materials. Such recovered materials were defined as circular

resources. In this chapter, several 'circular resources' were discussed through real-life full scale case studies of (recently developed) circular chains within the water sector.

## 12.6 EXERCISES

**Exercise 12.1:** Table 12.1 shows the waste management hierarchy. Provide at least two examples per step in the waste hierarchy ladder for the water sector as a whole. Can you provide two examples for each of the following sectors within the water industry: (i) drinking water production; (ii) municipal wastewater management and industrial (waste) water management?

**Exercise 12.2:** The most commonly used coagulants in drinking water treatment are iron salts (either with chloride or sulphate as counter anion) or aluminium salts in the form of aluminium sulphate (often referred to as alum) and Poly-Aluminium-Chloride (PAC). The choice differs depending on the region. For example, in Australia alum is predominantly used, whereas in countries such as the Netherlands and the US, iron-based salts are used more often. The latter is often directly related to the price of the coagulant, as both types of coagulants are capable of reaching desired water quality standards. In some regions alum is cheaper and readily available and in some iron salts are cheaper and readily available (i.e., the presence of iron and alum smelters greatly affect the price). In the context of 'circular resources', despite the fact that for your location iron salt coagulants to be used in drinking water treatment are 30% more expensive than alum-based salts, provide several arguments why iron-based salts ultimately would be considered the best choice for the urban water infrastructure at large?

**Exercise 12.3:** In the question above, you have provided several reasons why the choice of iron-based coagulants would be preferable for the urban water infrastructure at large. However, you may have given a different answer if you were the OH&S manager of the drinking water plant. Describe the OH&S concerns that are associated with transport, handling and storage of concentrated chemicals.

**Exercise 12.4:** The first implementation of the waste management hierarchy dates back to 1975 when it was included in the Waste Framework Directive (1975/442/EEC), and ever since has become one of the key pillars of environmental regulation that has been embedded in various national regulatory principles and guidelines as well international treaties and covenants. Nevertheless, as witnessed by our current way of wastewater management, in many instances the waste management hierarchy is not followed. Provide at least three reasons why this is the case.

**Exercise 12.5:** A drinking water utility uses alum as coagulant at a large-scale drinking water treatment plant (i.e., 500,000 PE). Currently, the produced sludge is stored on-site since regulation allows it and it is from an economic point of view (by far) the cheapest option. Moreover, there is sufficient space to store the sludge for another 30 years. Nevertheless, the utility is afraid that the regulation will change to prohibit on-site storage. Calculate the amount of sludge produced on a yearly basis used by the water utility and the financial impact it would have in case the sludge would need to be landfilled. In your answer, assume an alum dosing rate of 7 mg Al<sup>3+</sup>/L (see Chapter 3 for more detail), a daily water consumption of 130 liter per person per day, a sludge moisture content of 70% and a landfill gate fees of \$100 dollar per ton product (i.e., thus wet ton sludge). What about the situation where landfilling is not allowed?

## 12.7 DISCUSSION QUESTIONS

**Question 12.1:** What is the large-scale potential of iron-based coagulants from groundwater? (drinking water sector, industrial uses): Consider the production of iron-based coagulants from ground water. Look up the following information for the Dutch situation: (i) total amount of drinking water from



surface water treated by means of coagulant dosing; (ii) total amount of iron recovered from treatment of ground water? Based on this, can you determine the overall market potential of iron-recovery-to-coagulant production via this route? Can you identify any potential hurdles in terms economic, social acceptance and hygiene?

**Question 12.2:** Worth the trouble of taking such a risk? (utility management, leadership): As the innovation manager of a large water utility, you are in charge of reorganising the existing water infrastructure from its current situation to a more circular approach within a timeframe of 15 years. You have heard of several success stories of water recycling (see Chapter 4). You are somewhat enthusiastic about such an approach but you are wondering why you would take such a risk. While successful implementations of water recycling are plenty, there is a risk of not getting sufficient support from the community as there is still scepticism from people within the community? You are asked to give a presentation to the board of directors in which you evaluate the current status and justify your masterplan. What are your key considerations/motivations with respect to your decision? Furthermore, what in your opinion will be the most important challenge of water recycling: technical, economic or social acceptance? How can you minimise the risk of failure?

**Question 12.3:** Who is in the lead: government, water sector or commercial market? (leadership, drivers for innovation): Resource scarcity and sustainable use of resources is a societal challenge; ultimately it affects the community at large and our future generations. Changing to a (more) circular use of resources in general is a wise thing to do. This demands breaking with the linear economy. As described in this book, this requires a paradigm shift from the 'linear' to the 'circular' economy. The latter will not be an easy and straightforward task. You can imagine that adopting such a circular value chain will entail certain risks for the water utilities; in fact it can be argued to be a somewhat risky and challenging path. So, should the government take the initiative to stimulate or even force the creating of new circular value chains? By legislation, taxation or subsidies? Or should the initiative lie within the water sector itself? In your answer, keep in mind that for most companies in this value chain resource recovery is often not their primary focus (i.e., quite obviously, for drinking water companies this is first and foremost producing drinking water of high quality).

**Question 12.4:** Production of ultra-pure water from domestic wastewater effluent (industrial uses, drivers, regulation): The Water Re-use Case study the Ultra-Pure (UPW) Water Factory Emmen has been in operation since 2010 (Figure 12.2). This water reclamation plant produces up to 10 ML/day of ultra-pure water that is subsequently used by Shell-NAM for oil extraction. Discuss what might drive this type of collaboration between the water utility and Shell. In particular, focus on: (i) the drivers for the water utility to collaborate with Shell and (ii) the drivers for Shell to collaborate with the utility and use wastewater effluent? Do you think they are purely economically driven? Do you think that there also drivers for the local government and/or national government to support (financially) such an innovative project?

**Question 12.5:** Increasing the energy self-sufficiency (industrial uses, drivers, regulation): Biogas production by means of anaerobic digestion and subsequent beneficial on-site production of electricity (and heat) has several advantages. In some cases, applying digestion is not the most cost-effective method (under the current electricity and natural gas prices). Nevertheless, even in these situations anaerobic digestion is still applied. Discuss what the rationale for such a decision could be. In your answer include sustainability, green image, self-sufficiency, independency, regulation and potential synergy with agricultural and municipal solid waste management (e.g., co-digestion).

**Question 12.6:** Multiple re-use of iron in urban water management (industrial uses, drivers, utility management): Despite that direct dosing of iron-rich sludge to sewers for sulphide control is successfully applied at full-scale, some utilities have indicated that the feasibility may depend on the

origin of the sludge. Provide several examples of what the reasons for the latter could be. In your answer discuss the following aspects: (i) transport distance; (ii) configuration/capacity downstream wastewater treatment plants; and (iii) presence of impurities.

**Question 12.7:** Putting resource recovery from water in the sustainability context (long-term thinking, global context, sustainability): It is nice to have ambitious goals as set out by various water utilities to become more sustainable. However, the term ‘sustainability’ is rather broad. To illustrate this, the most commonly used definition of sustainability is the so-called ‘Brundtland’ definition:

‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’.

How would a ‘sustainable’ situation with respect to wastewater management in the city you live look like by the year 2050? This sounds like an easy question, but in fact is very complex and moreover very important (i.e., you can only find the right answers/solutions if you know what you are looking for!). What does the term ‘needs’ mean? In your response describe the technical, social, economic, political and environmental characteristics. Finally, think about the question how resource recovery from wastewater fits in this context and what are the limiting factors (or slowing down) for the widespread adoption of resource recovery. Are these technological, economical or are these more social/political related.

**Question 12.8:** How to define/explain the circular economy (regulation, sustainability, critical thinking): The term circular economy has become very popular in recent years. However, many definitions and interpretations of this concept exist. Define the term circular economy in your own words, in a maximum of 250 words. After defining the ‘circular economy’ in your own words, read the following manuscript:

Ghisellini, P., Cialani, C. & Ulgiati, S. 2016 A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, **114**, 11–32. After reading this manuscript, did your understanding and/or view on the definition and the importance of the circular economy change?

**Question 12.9:** Policy drives innovation? (regulation, drivers for innovation). Do you think that policy makers are important stakeholders/actors in relation to the creation of a circular economy? In your opinion, how can policymakers stimulate efficient (re-)use of resources in our society? And what if you only look at the water industry, would your answer be different?

**Question 12.10:** How to define/explain recycling’, ‘re-use’, ‘recover’ of the materials’ (critical thinking): Besides the multiple ways of looking at the use and pathways of resources and materials in the water sector by means of the waste management hierarchy, the terms and definitions that describe these pathways (e.g., re-use, recycle and recover) need to be clearly understood and differentiated. For instance, the terms ‘re-use’ and ‘recycling’ are often used to describe the ‘good use’ of a residual, but both terms in reality mean something completely different. Recycling refers to the process of converting waste into new materials, while re-use refers to the re-use of a material in its original function. It is therefore important to get a fundamental understanding and detailed knowledge of what these different terms really comprise. In a practical situation, it is therefore strongly advised to inquire with the client, regulator or customer, to what they are referring to in terms of ‘recycling’, ‘re-use’, ‘recover’ of the materials in order to avoid any confusion and/or misunderstanding. Define the ‘recycling’, ‘re-use’, ‘recover’ of the materials in your own words and in particular highlight the differences between these different terms.

**Question 12.11:** Multiple re-use of iron in urban water management (leadership, drivers, and utility management) Hydrogen sulphide ( $H_2S$ ) induced sewer concrete corrosion is a notorious and very costly issue for water utilities worldwide. Besides, the emission of  $H_2S$  from sewer manholes is a threat for sewer workers. Moreover, its obnoxious odours result in frequent complaints from the surrounding community. All of the above need to be dealt with appropriately at all times. In principle, iron-rich drinking water sludge you have produced upstream during drinking water production can theoretically be dosed to sewer networks as a means to control hydrogen sulphide. Imagine yourself being the lead engineer of the wastewater utility managing the sewer network and downstream WWTP; do you think it is better to use the drinking water sludge instead of fresh chemicals, or a combination of both? In your answer discuss the terms reliability, community engagement, potential negative side-effects and integrated urban water management.

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