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Alternative water supply - State of the art

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Report

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Preface

This report has been written at DTU Environment within the “Sammen om fremtidens vand” project financed by Vandsektorens Udviklings- og Demonstrationsprogram by the Dansk Vand- og Spildevandsforening. It is a deliverable to all project partners (Fors A/S, Berendsen Textil Service, Kalundborg Forsyning, Boligselskabet Sjælland, Fr. Dahlgaard A/S).

Lyngby, June 2019

Indhold

1. Introduction and background

Water demands are almost exclusively covered by groundwater in Denmark. By utilizing alternative water sources, the pressure on groundwater resources can be reduced. Polluted groundwater, saline water and brackish water, wastewater and rain- and stormwater can be treated to meet drinking water criteria when adequate technologies are used. However, by defining quality demands according to the use, treatment requirements can be reduced. The Danish EPA defines water with a quality below drinking water standards for non-potable uses as "secondary water".[1] Secondary water has gained interest in Denmark, with several projects and studies outlining potentials and requirements.[1,2]

This report outlines current approaches and technologies to use alternative water sources and make different water qualities available to customers. It is intended to be an inspiration for developing strategies for alternative water supply in Denmark, but does not provide concrete recommendations. The focus lies on secondary water, i.e. water for non-potable use, for application in buildings, for irrigation and industry. Agricultural reuse and groundwater recharge are not considered in this report.

The initial screening of technologies was done based on the book by Rygaard et al. (2009)[3] . We used an internet search and literature review to compile recent technologies and examples of applications.

We classified the different approaches and technologies according to the water source they utilize, following the classification of the Danish EPA into groundwater, saline water, groundwater and stormwater.[4] Besides the source, technologies can also be classified according to their spatial scope: Water can either be treated centrally before distribution to whole cities or neighbourhoods, or it can be treated locally on site. The deciding factors for choosing a technology are the initial source, the required water quality and the required capacity.

Alternatively to substitution to reduce pressure on groundwater resources, water demands can be reduced. This can e.g. be done by installing water saving appliances or by targeted planning.[3,5] These approaches are not discussed further in this report, as the focus lies on water supply instead of savings.

2. Alternative water sources and exemplary cases

Besides clean groundwater, other water sources can be used to cover both potable and non-potable water demands: polluted groundwater, saline water, wastewater and rain- and stormwater. In the following sections, different approaches to treating and using these alternative sources are explained. Examples of implemented systems are used to illustrate the application of the different technologies.

2.1 Polluted groundwater

While water supply in Denmark is almost solely based on groundwater resources currently, polluted aquifers can be a source of secondary water. Since pollution levels are usually low, very limited treatment is required to meet high water quality standards. Pollutants in groundwater can lead to clogging or corrosion of pipes, which simple treatment can prevent.[1] Polluted groundwater is often used for cooling, which demands only limited treatment.[1,2]

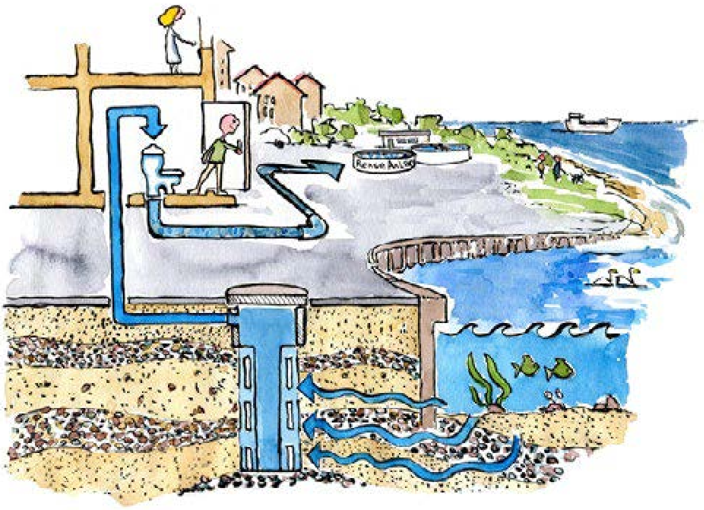

Figure 1. Schematic sketch of the circulation of brackish groundwater in Nordhavn, Denmark.[6]

In Nordhavn, Denmark, brackish groundwater is used for flushing toilets after aeration and sand filtration (Figure 2).[7,8] The local water utility in Esbjerg, Denmark, delivers polluted groundwater to industries, which are then responsible for treatment to achieve the required water quality. In Copenhagen, Denmark, groundwater levels have to be lowered. The pumped groundwater was used for desulphurization at the Amagerværket power plant after sand and membrane filtration.[2] Untreated, polluted groundwater is a water supply for so-called “vandkiosker” in Copenhagen, which provide water for watering green areas.[2]

2.2 Saline water

When saline water or brackish water is used as process water, often only simple treatment is required.[9] HOFOR is providing district cooling in Copenhagen, Denmark, using cold water from the harbour without treatment (Figure 3).[10] At Amagerværket, Denmark, saline water is desalinated before use as process water.[11] Saline water can also be used at building scale for heating and cooling, as e.g. done in the Exploratorium, a museum in San Francisco, US.[12,13]

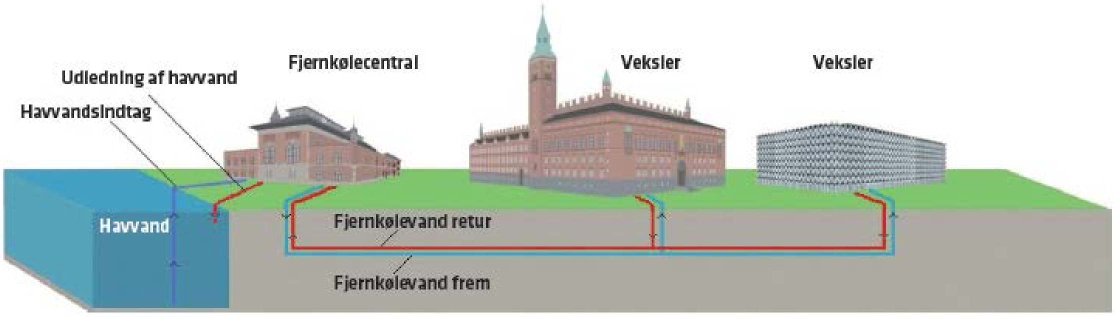

Figure 2. Schematic saline water based district cooling system.[10]

When saline water is desalinated, drinking water quality can be achieved. This is for example done in Singapore, where reverse osmosis is utilized. Electro-deionisation, which has significantly lower energy demands than reverse osmosis, has been tested in pilot plants in Singapore and is planned to be implemented at larger scale. Biomimetic membranes enhanced by aquaporins are explored as an option to further reduce energy consumption.[14]

2.3 Wastewater

To reclaim wastewater from households and industries, it is often treated in a central treatment facility. The first step is conventional treatment, which includes screening, settling, biological activated sludge process, coagulation and removal of particles, organic compounds and nutrients.[3] The following advanced treatment depends on the required water quality. For non-potable use, chemical coagulation,[3] filtration,[3,15] purification with activated carbon,[3,15] UV treatment[16] and disinfection with chlorine[17] are possible treatment options. Membrane bioreactors can be used for pressure driven filtration, including dynamic membrane filtration, micro-, ultra- and nanofiltration (Figure 5).[3,9,18,19] Anaerobic fluidized bed membrane bioreactors can produce non-potable water while simultaneously recovering energy.[9]

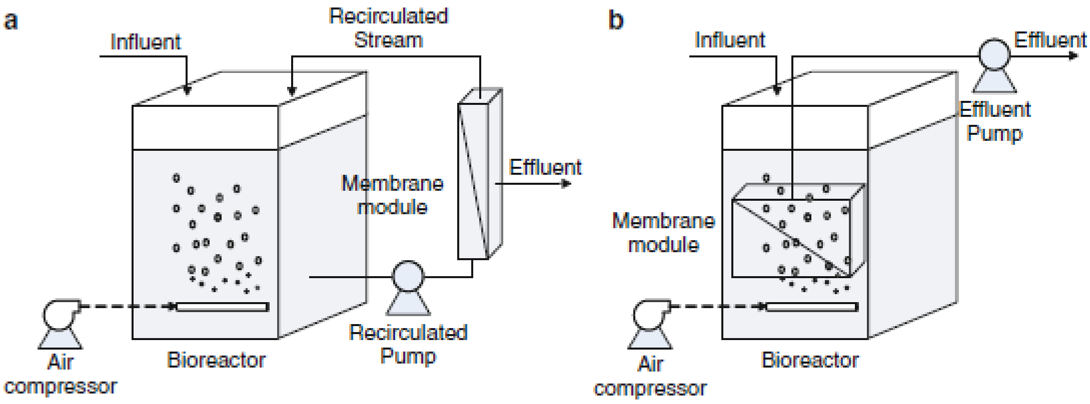

Figure 3. Two types of membrane bioreactors: a) side-stream reactor, b) submerged reactor.[19]

Additional treatment is required to achieve drinking water quality, e.g. micro-, nano-, or ultrafiltration, membrane bioreactors or reverse osmosis.[3] Premade membrane bioreactor modulus specifically for decentral implementation can be purchased, e.g. the BioBooster developed by Grundfos, which uses aerobic treatment and ceramic or polymer discs for filtration (Figure 6).[20]

2.3.1 Wastewater from households and offices

Simple decentral treatment even at household level is possible when the pollution levels in wastewater are limited. Grey wastewater from kitchens, bathrooms and washing machines has lower levels of organic matter and nutrients than ordinary wastewater. If collected separately from black wastewater, it can then be reused with only simple, decentral treatment, e.g. filtration and disinfection.[21,22] Australian legislation even allows for grey wastewater to be used directly for garden irrigation and toilet flushing without treatment.[13]

On a very small scale, wastewater from showers can be recirculated and used for showering again after filtration and UV treatment (Figure 4).[16] Rainwater harvesting on a larger building scale allows for more diverse applications: In the Millennium Dome in London, UK, water from sinks is reused for toilet flushing after passing a biological air filter.[3] In the San Francisco Public Utilities Commission Headquarters, all wastewater (both black and grey) is treated in artificial wetlands before reuse for toilet flushing.[12] Membrane bioreactors are a common choice for decentral wastewater treatment in large buildings because of their limited space requirements, high yield and high achieved water quality, as e.g. utilized in the Fremont Mixed-use Tower in San Francisco, US.[12]

Figure 4. Flow loop shower for direct wastewater reuse after filtration and UV treatment.[16]

Wastewater can be treated in combination with stormwater, as e.g. done in Battery Park City, a redevelopment area in New York City, US. Micro-filtration membranes, UV disinfection and biological nitrogen removal are used to before reuse for toilet flushing, laundry, irrigation and cooling.[23]

2.3.2 Wastewater from industry

Decentral treatment of wastewater is usually used at large industries or hospitals and utilizes the same processes as in central treatment facilities. Arla Foods uses process water for cooling and cleaning after membrane bioreactor treatment in a dairy factory in in Fredericia, Denmark.[24] Nørager Mejeri uses process water from dairy production for cleaning and flushing after ultrafiltration, and Thise Mejeri recirculates process water after reverse osmosis treatment (Figure 5).[24] In Tokyo, Japan, an activated sludge process or membrane bioreactors are used for decentral treatment at building level for non-potable use.[3] In a pilot project, Berendsen Textil Service A/S recirculates laundry wastewater after a treatment train consisting of different tanks for flocculation, flotation and buffering, filters, reverse osmosis and UV (Figure 6).[25] If capacity allows, other sources of secondary water, e.g. rainwater, can be treated at the already installed decentral treatment facilities.[1]

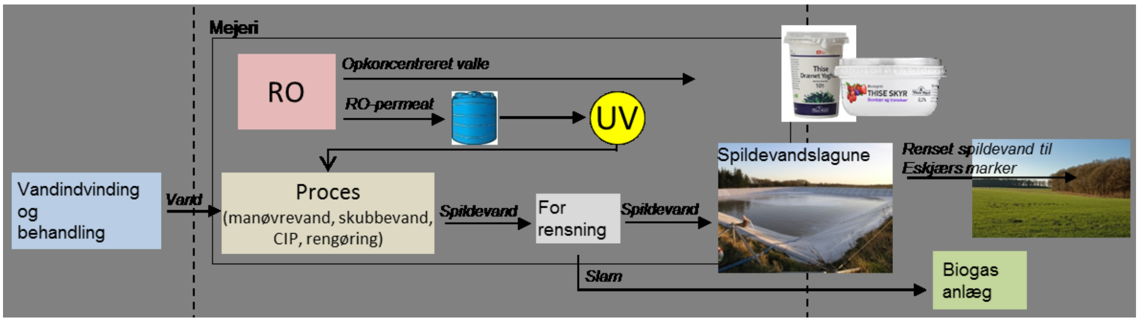

Figure 5. Schematic sketch of the water circle at the Thise Mejeri dairy factory.[24]

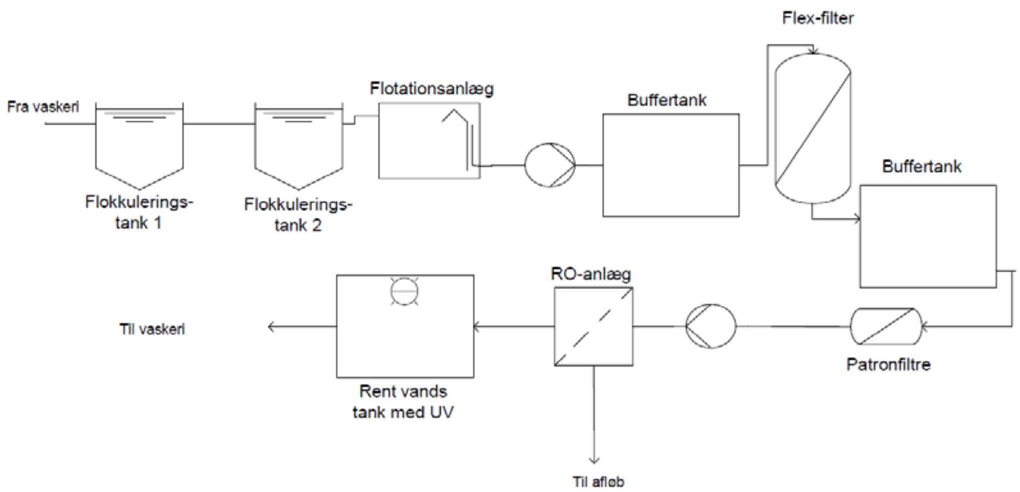

Figure 6. Schematic sketch of the water circle at the pilot plant at Berendsen Textil Service A/S.[25]

Decentral industrial wastewater treatment can also create additional benefits, as e.g. shown for the Carlsberg brewery in Fredericia, Denmark. The wastewater from the brewing process has a high COD content, which can be used to produce biogas through anaerobic treatment before aerobic treatment. Using reverse osmosis, oxidation and disinfection, the wastewater can be treated to meets quality standards required for reuse as process water at the factory.[26]

Industries and production plants often require different water qualities in different processes. This is e.g. the case at the HKScan chicken feet production factory in Denmark, for which it was suggested to reuse lightly polluted water from the last step of the processing line at the beginning of the line for initial cleaning of the feet.[27] Another way to optimize the reuse of wastewater is to connect different industries with different quality demands, as e.g. done in Kalundborg. Amongst others, lightly polluted process water from the production of ultra clean water at Novo Nordisk is reused at other utilities and cooling water from Statoil is reused for boilers at the Asnæsværket power plant.[28]

2.3.3 Combined wastewater from households and industries

In Singapore, a combination of microfiltration, reverse osmosis and UV treatment is utilized to recover 75% of household and industrial wastewater, and electrodialysis reversal-reverse osmosis is explored as an option to further increase the recovery rate.[14] At a large chemical plant at the Gulf Coast, US, effluent from a municipal wastewater treatment plant is treated using ultrafiltration and reverse osmosis before reuse at the plant.[29] Other industries have lower water quality demands, e.g. refineries: In Hampton Roads, US, municipal wastewater is treated using biological nitrification before reuse as cooling and process water at the Yorktown Refinery.[30]

When wastewater is treated centrally, it usually is redistributed in separate pipes, as e.g. done in the Irvine Ranch Water District, US, for more than 30 years.[30] In California, US, reclaimed wastewater of non-potable quality is also delivered to households in trucks if no separate pipe system is in place.[17] If reclaimed wastewater is used as drinking water, it often is mixed with other water sources or infiltrated to groundwater first, as e.g. done in Costa Brava, Spain.[3]

2.4 Rain- and stormwater

Rainwater (from roofs) and stormwater (from roads and other impervious areas) have been identified as a secondary water source with large potential with limited treatment requirements by the Danish EPA.[1] Simple filtration to remove particles is often sufficient when reused for non-potable uses, as recommended by the Danish Technological Institute.[31] This is in line with other regulations, e.g. by the Rainwater Harvesting Association of Australia.[32] A guideline developed by the Los Angeles County Department of Public Health additionally recommends disinfection.[33] The German Environment Agency determines that runoff from roofs made of copper, zinc or using bitumen should not be used. It further determines that untreated rainwater is safe for toilet flushing, but should not be used for laundry of people with a suppressed immune system due to risk of bacterial contamination.[34]

Currently, rainwater harvesting is primarily implemented in residential buildings, and is mainly used to provide water for toilets and washing machines, as e.g. done in Folehaven, Denmark.[2,35] In Stenløse Syd, Denmark, reuse of rainwater for toilet flushing was made mandatory already during the development of the new residential area. It is collected in underground tanks after filtration.[2] This is in line with a guideline by the Danish Technological Institute, which specifies that roof runoff should be filtered, e.g. with cyclone or vertical filters, before collection in a tank (Figure 6).[31] Off-the-shelf systems for rainwater reuse in households are available by different providers, e.g. Nyrup Plast, regnvandsTanken and GRAF (Figure 7). If solely used for garden irrigation, simple overground tanks can be connected to the downpipe via a simple filter (Figure 7).

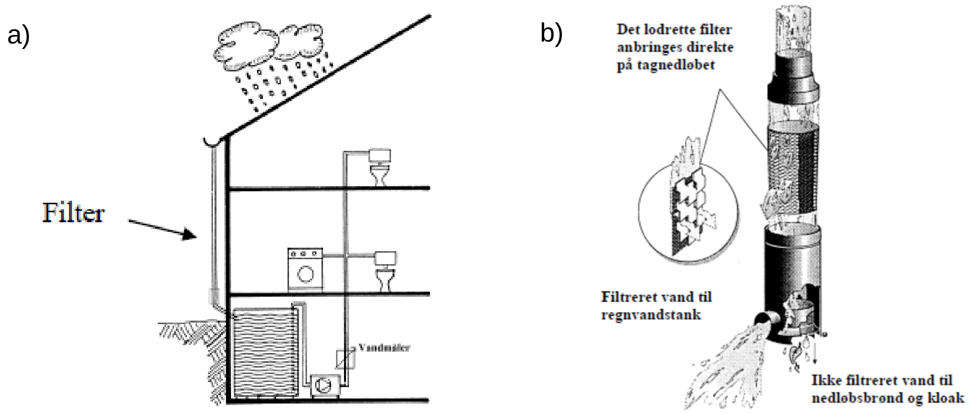

Figure 7. Schematic sketch of a) a local rainwater harvesting system with a basement tank for toilets and washing machines and b) a vertical filter.[31]

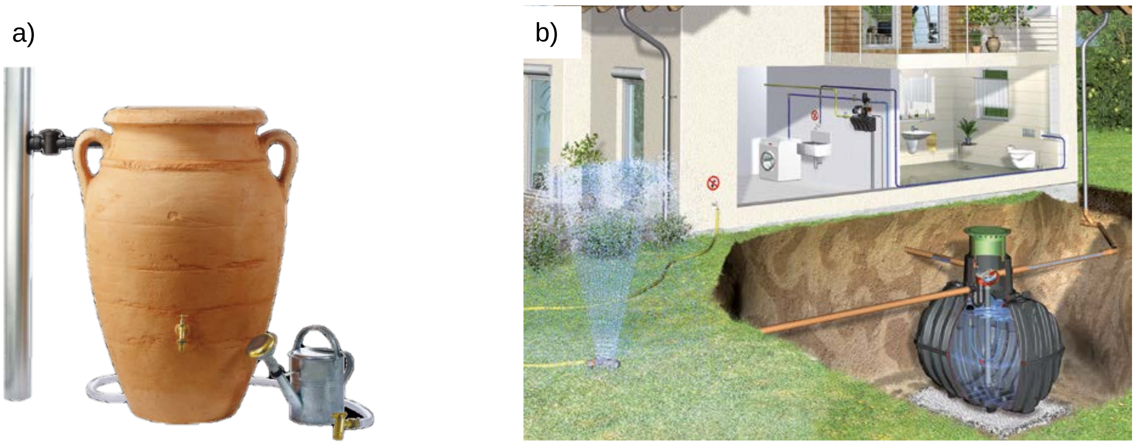

Figure 8.Off-the-shelf systems by GRAF for a) overground rainwater tanks for garden irrigation[36] **and b) subsurface rainwater harvesting for non-potable reuse**[37]

Larger buildings provide potentials for stormwater collection in tanks and reuse, as e.g. done in the San Francisco, US: In the Public Utilities Comission Headqauerters, rainwater used for irrigation of green areas and in the museum “The Exploratorium”, toilets are flushed with roof runoff.[12]

Rain- and stormwater can also be collected in central tanks or basins. In Nye, Denmark, rain- and stormwater is collected in a green surface basin, where pollutants are partially removed through sedimentation before ultrafiltration and UV treatment at a central plant. The water is then redistributed to households for toilet flushing and laundry.[38] Farago et al. (2019) suggested hydrogen peroxide disinfection as a possibility to replace UV treatment.[39] In Greve, Denmark, rainwater is used for irrigation of green areas in a residential area without treatment.[2] In Berlin, Germany, a combination of green roofs, sand filters and microfiltration is used to purify rain- and stormwater from Potsdamer Platz. The water is then used for flushing toilets, irrigation and artificial wet areas.[3] Artificial and natural wetlands and reed beds are used for cleaning stormwater to non-potable quality in Salisbury, Australia, before injection into a limestone aquifer, from which it is used for different non-potable applications.[40]

Stormwater is mainly used for irrigation or non-potable uses in households in Denmark. This trend can also be seen in other parts of the world, e.g. Australia, where irrigation demands are high and often covered by centrally collected stormwater.[41] Only few projects for reuse of rain- and stormwater for industry and other purposes are established in Denmark so far. In Tårnby, DK, it is planned to use rain- and stormwater for flushing sewers after UV treatment or chlorination to remove bacteria.[2] Berendsen Textil Service A/S is using rainwater from a 400m^2 large roof area for laundry after filtration, chemical disinfection and UV treatment.[42,43] In Kalundborg, Denmark, rainwater is mixed with surface water and used for cooling at industries.[28] Rain- and stormwater can also be used as drinking water, as e.g. done in Singapore, where water is collected in 17 reservoirs before treatment.[14]

3. Non-potable applications and system configurations

Secondary water can be used for a wide range of non-potable application, as shown in the examples described in section 2 (Table 1). Theoretically, any water quality can be achieved with advanced treatment, i.e. the use of secondary water is not restricted. In reality though, the applications are limited by their economic considerations and initial and required water quantity and quality. Rain- and stormwater and grey wastewater are often only lightly polluted, making decentral reuse at household level feasible. Black wastewater requires more advanced treatment only feasible at larger scale, enabling reuse at industries with large water demands. Saline water can easily be used as a source for cooling and heating both for industry and buildings. Furthermore, the water source used for non-potable demands is often determined by given boundary conditions, e.g. availability of polluted groundwater or proximity to the sea.

Table 1. Non-potable applications of water from different alternative sources found in the example cases. The number indicates the section of this report where additional information can be found.

Application	**Source**			
	Polluted groundwater	Saline water	Wastewater	Rain- / stormwater
Buildings				
Toilet flushing	2.1		2.3.1	2.4
Laundry			2.3.1	2.4
Cooling / heating		2.2	2.3.1	
Irrigation				
Private gardens			2.3.1, 2.3.3	2.4
Public areas	2.1		2.3.1	2.4
Industry				
Cooling / heating	2.1	2.2	2.3.2, 2.3.3	2.4
Process water	2.1	2.2	2.3.2, 2.3.3	2.4

When a decision is made regarding the water source, numerous approaches and technologies exist, as described in section 2 (Table 2). The case studies show that a combination of technologies is usually used to treat secondary water to meet quality standards defined by the intended application (Appendix A.1). Regulations regarding water quality standards for specific purposes vary between countries, and sometimes even within countries.

Table 2. Overview of treatment technologies and their application for treating secondary water from different sources. N indicates that water can be used for non-potable applications, while D indicates that drinking water can be achieved.

Treatment	**Source**			
	Polluted groundwater	Saline water	Wastewater	Rain- / stormwater
No treatment	N	N	N	
Aeration	N		N	
Micro- /ultrafiltration			N	N
Sand filtration	N			
Membrane filtration	N			
Mechanical filtration				N
Biological air filtration			N	
Membrane bioreactors			N/D	
Reverse osmosis		N/D	N/D	N/D
Conventional wastewater treatment			N	
Chemical coagulation			N	
Flocculation			N	
Flotation			N	
Activated carbon purification			N	
UV treatment			N	N
Chemical disinfection			N	N
Activated sludge process			N	
Oxidation			N/D	
Surface basin				N
Biotopes				N
Aquifer injection / infiltration			N/D	N/D

4. Conclusions

Polluted groundwater, saline water, wastewater and rain- and stormwater are alternative sources for water supply. While treatment up to drinking water quality requires significant resources, water for non-potable applications can often be provided with limited treatment. The treatment depends both on the initial and the required quality, and a combination of different technologies is usually used. The definition of use-specific requirements allows for targeted treatment, while at the same time requiring a separate distribution network besides the drinking water system.

Rain- and stormwater and grey wastewater are often only lightly polluted, allowing reuse even at household level using only simple treatment, e.g. filtration. Saline water can easily be used for cooling and heating at building, industry and district level. Black wastewater requires more advanced treatment, often making central treatment and redistribution to industries or other applications with large water demands a feasible options. The connection of different sources and users enables more wide applications and can increase efficiency, e.g. if lightly polluted process water is reused for cooling.

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Appendix

A.1. Overview of exemplary systems

Case	Treatment	Application
Polluted groundwater		
Nordhavn, Copenhagen, DK	Aeration, sand filtration	Toilet flushing
Esbjerg, DK	No treatment	Process water, cooling
Vandkiosker, Copenhagen, DK	No treatment	Irrigation
Amagerværket, Copenhagen, DK	Sand filtration, membrane filtration	Process water
Saline water		
Copenhagen, DK	No treatment	Cooling
Singapore	Reverse osmosis	Drinking water
Amagerværket, Copenhagen, DK	Desalination	Process water
The Exploratorium, San Francisco, US	Microfiltration, UV treatment	Heating, cooling
Wastewater		
Costa Brava, Spain	Conventional treatment, coagulation, flocculation, sand filtration, UV treatment and infiltration	Drinking water
Arla Foods, DK	Membrane bioreactor	Cooling, cleaning
Nørager Mejeri, DK	Ultrafiltration	Cleaning
Thise Mejeri, DK	Reverse osmosis	Process water
Tokyo, Japan	Membrane bioreactor	Toilet flushing, irrigation
Berendsen Textil Service A/S, DK	Flocculation, flotation, reverse osmosis, UV treatment	Process water
Millenium Dome, London, UK	Biological air filter	Toilet flushing
Australia	No treatment	Irrigation, toiled flushing
Kalundborg, DK	No treatment	Cooling, boilers at power plant
Singapore	Conventional treatment, microfiltration, reverse osmosis, UV treatment	Drinking water
San Francisco Public Utilities Commission Headquarters, US	Artificial wetlands	Toilet flushing
Fremont Mix-use Tower, San Francisco, US	Membrane bioreactor, disinfection	Toilet flushing, irrigation
Battery Park City, New York, US	Micro-filtration membranes, UV disinfection, biological nitrification	Toilet flushing, laundry, irrigation, cooling
Chemical plant, Gulf Coast, US	Ultrafiltration, reverse osmosis	Process water
Rain- / stormwater		
Kalundborg, DK	No treatment	Cooling
Folehaven, DK	Mechanical filtration	Toilet flushing, laundry
Stenløse Syd, DK	Mechanical filtration	Toilet flushing

Tårnby, DK	UV treatment, chemical desinfection	Sewer flushing
Berendesen Textil A/S, DK	Mechanical filtration, chemical disinfection, UV treatment	Laundry
Nye, DK	Surface basin, ultrafiltration, UV treatment	Toilet flushing, laundry
Greve, DK	No treatment	Irrigation
Berlin, Germany	Green roofs sand filtration, microfiltration	Toilet flushing, irrigiation
Salisbury, Australia	Wetlands, reed beds, aquifer injection	Irrigation, toiled flushing, process water
Singapore	Reverse osmosis	Drinking water