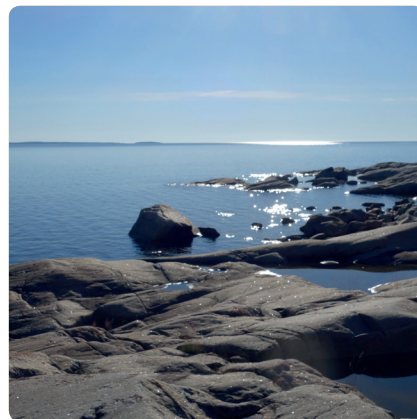


Advanced wastewater treatment for separation and removal of pharmaceutical residues and other hazardous substances

Needs, technologies and impacts

A government-commissioned report

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Orders

Phone: +46 (0)8-505 933 40

Fax: +46 (0)8-505 933 99

E-mail: natur@cm.se

Address: CM Gruppen AB, Box 110 93, 161 11 Bromma, Sweden

Online: www.naturvardsverket.se/publikationer

The Swedish Environmental Protection Agency

Phone: +46 (0)10-698 10 00 Fax: +46 (0)10-698 16 00

E-mail: registrator@naturvardsverket.se

Address: Naturvårdsverket, 106 48 Stockholm, Sweden

Online: www.naturvardsverket.se

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Foreword

As commissioned by the government of Sweden, the Swedish Environmental Protection Agency hereby presents its report outlining the prerequisites for using advanced treatment at wastewater treatment plants to separate and remove pharmaceutical residues. The report analyses the need for advanced treatment, the technical solutions available including their advantages and disadvantages, and other implications of the use of advanced treatment.

The commission was carried out in close dialogue with the Swedish Agency for Marine and Water Management, the Swedish Chemicals Agency and the Swedish Medical Products Agency. Input was also received from the Swedish Water & Wastewater Association, and background material and conclusions were anchored with a reference group associated with the commission. We would like to warmly thank everyone for their cooperation.

The work at the Swedish EPA was conducted by Anna Maria Sundin, Linda Linderholm, Britta Hedlund, Kerstin Bly Joyce and Karin Klingspor (project manager).

The Swedish Environmental Protection Agency, April 2017

A handwritten signature in black ink, appearing to read 'Kerstin Bly Joyce', is positioned below the text of the foreword.

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1. Overall assessment of the prerequisites for using advanced treatment for removal of pharmaceutical residues from wastewater

The Swedish Environmental Protection Agency (EPA) has determined a need to introduce advanced treatment for pharmaceutical residues in wastewater. An additional benefit of such a treatment is that it would also include the treatment of other hazardous substances.

The extent to which pharmaceutical residues risk becoming a problem depends on local conditions such as the sensitivity of the receiving waters. While this is an important variable to consider, the Swedish EPA believes that the sensitivity of the receiving waters should not be the only consideration when setting requirements for treatment. The amount of released pharmaceutical residues and long-term effects should also be considered in decision making and justification. The investment and operational costs of introducing advanced treatment depend in part on the size and current capacity of treatment facilities, which is why size limitations can be an additional consideration when setting requirements.

The need is justified broadly based on the risk of long-term effects of a constant exposure to low levels of pharmaceutical residues in the aquatic environment with possible adverse effects on aquatic organisms. Also, some pharmaceutical residues are persistent and will remain in the environment and accumulate in biota. Because future impacts on the environment and human health are difficult to predict, the introduction of advanced treatment can be justified on the basis of the precautionary principle as per the general rules in the Swedish Environmental Code. Several studies have shown that pharmaceuticals can have adverse effects in the aquatic environment, including endocrine-disrupting effects and the potential to contribute to the spread of antibiotic resistance.

Furthermore, one study has shown that the calculated concentrations¹ of several pharmaceutical residues in receiving waters exceed established assessment criteria²

¹ Based on data from environmental monitoring, Swedish EPA screening programme and other studies. See also Chapter 2.3.

² One way to assess the risk of impact is to compare the concentrations of pharmaceutical residues with the values in the assessment criteria for river-basin-specific pollutants, which are currently available for three pharmaceutical substances. The values are based on an estimate of the concentrations that do not present any unacceptable risk to impacts on the aquatic environment.

and effect levels³ in several water bodies at wastewater treatment plants (WWTPs). This indicates that there is a need to investigate further whether such receiving waters meet the requirements for good ecological status. In addition, a screening study has detected 15 out of 101 pharmaceutical substances in such high concentrations in the surface water of the recipient that they are expected to have a pharmacological effect⁴ in fish exposed to the water.

The question of which WWTPs and how many of them require advanced treatment cannot be determined with existing evidence. However, the Swedish EPA has identified important factors for prioritising the necessary actions. When implementing additional treatment steps for pharmaceutical residues and other hazardous substances, the following local conditions should be considered:

- The amount of pharmaceutical residues and other persistent pollutants released into receiving waters
- The water recharge rate of the receiving waters, where the receiving waters with low initial dilution and a low water recharge rate risk reaching the threshold values stated in the assessment criteria for river-basin-specific pollutants and effect levels
- The presence of several WWTPs that discharge to the same receiving water body
- The receiving water body's sensitivity, such as ecological sensitivity
- Fluctuations in water recharge rate over the year in the receiving waters, and variations in effluent volumes from the WWTP

Technologies are available for the advanced treatment and removal of pharmaceutical residues from wastewater. The combination of different technologies that use various treatment mechanisms – physical processes, oxidative methods, biological methods and adsorption – result in a nearly complete removal of all pharmaceutical substances from the wastewater. In addition, these technologies could contribute to the removal of other hazardous substances and to a reduction in the spread of antibiotic resistance, depending on which technology is implemented. It is important to select a treatment technology based on the current objective and on local conditions because each WWTP is unique.

Advanced treatment should be implemented as a complement to existing WWTPs. All technologies rely on a properly functioning main wastewater treatment process, a crucial factor to consider at smaller WWTPs that may lack an efficient system for the treatment of nutrients, organic substances and particles. Although all the technologies can be used at both small and large WWTPs, economies of scale and

³ In addition, there are other effect levels in the scientific literature that can be used to compare the levels of pharmaceutical substances and other hazardous substances found in the environment. The uncertainties surrounding the effect levels, however, are great.

⁴ The effect that a drug is intended to provide.

cost effectiveness can be achieved for installations at larger facilities. In general, larger facilities have more resources to ensure follow-up, process optimisation, and operation and maintenance of the facility. An effective treatment for the studied substances for facilities larger than 100,000 population equivalents (PE) can be achieved using several of the treatment techniques for less than 1 SEK/m³ based on certain assumptions. For smaller facilities (2,000–20,000 PE), the costs of certain treatment technologies are about 5 SEK/m³. However, the uncertainty in the calculations is considerably greater for smaller WWTPs. With the continued development of technologies, operational experience and more resource-efficient facilities, the cost structure will likely change over time.

The environmental costs associated with introducing advanced wastewater treatment are primarily related to increased energy consumption and chemical use. This negatively affects other national environmental quality objectives. Other environmental aspects to consider include the formation of residues. Some of the technologies involve contamination of the sewage sludge, which should be considered when choosing the technology and sludge strategy at the WWTP.

The introduction of advanced treatment brings both environmental and health benefits. Several studies have shown that pharmaceuticals can have adverse effects in the aquatic environment, including endocrine-disrupting effects and the potential to contribute to the spread of antibiotic resistance. The benefits for society are identified here, but it has not been possible to quantify the benefits of advanced treatment at the national level.

A number of drivers and obstacles have been identified for introducing advanced treatment at Swedish WWTPs. Drivers include the identified need in the local receiving waters, and new or additional treatment requirements that are expected. In regard to obstacles, the water and wastewater industry faces major challenges in the future, mainly in the form of greater investment needs. Piping needs to be replaced more often, and the requirements on wastewater treatment and the safe production of drinking water are increasing. These challenges affect smaller municipalities in particular. Municipalities included in collaborative solutions and regional cooperative efforts are expected to succeed in meeting future challenges more easily. Small municipalities with smaller budgets usually find it more difficult to finance advanced upgrades to their WWTPs beyond the legal requirements, since other investments tend to take priority for securing long-term sustainability.

All in all, a reasonable trade-off needs to be made in each individual case, where the need for and the benefits of introducing advanced treatment are weighed against the costs.

Continued efforts are needed

The need to introduce advanced treatment at WWTPs varies. Today, we do not know how many facilities or which ones should be prioritised. A solid knowledge base must be built up, and because advanced treatment is still under development it should be implemented sustainably, for example through multi-stage deployment. The Swedish EPA proposes that the Government further investigate steps towards implementing advanced treatment, starting where the need is greatest, as follows:

Step 1: Determine which WWTPs have the greatest need for advanced treatment of pharmaceutical residues.

Step 2: Determine the governance and controls necessary for implementing advanced treatment where the need is greatest, in a way that is socioeconomically efficient and fit for purpose.

2. Commission and implementation

2.1. The commission

In December 2015, the Swedish EPA was tasked by the Government to investigate the prerequisites for using advanced treatment to remove pharmaceutical residues from wastewater with the aim to protect the aquatic environment (see Annex 1).⁵

The commission includes analysing the need for advanced treatment, the technological solutions available including their advantages and disadvantages, and other consequences of the use of advanced treatment. The results were presented to the Government Offices on 1 May 2017.

2.2. Limitations

The commission has focused on WWTPs that serve a population of more than 2,000 people or that receive wastewater with a pollutant load corresponding to more than 2,000 PE. The reason for this limit, compared with the 20,000 people or PE specified in the commission, is that the same technologies are in principle relevant for all WWTPs greater than 2,000 PE, and it is worthwhile shedding light on the prerequisites for a larger number of the facilities. WWTPs greater than 2,000 PE also represent a natural limitation because they must obtain permits.

The commission does **not** include the following measures:

- Measures upstream of the WWTPs to reduce the release of pharmaceutical residues into the environment.
- Wastewater from industrial operations or animal husbandry that is not connected to municipal WWTPs.
- The management of sludge from WWTPs. However, the content of different pharmaceutical residues and other hazardous substances in the sludge resulting from advanced treatment (i.e., the impact on sludge quality) is taken into account.

The analysis of the advantages and disadvantages of different advanced treatment technologies takes into account the significance of other hazardous substances.

Treatment technologies deemed to be currently available on the basis of best available technology (BAT) are considered. Technologies considered to be under development are described more briefly.

⁵ Case NV-08854-15.

2.3. Implementation

The commission was carried out in close dialogue with the Swedish Agency for Marine and Water Management, the Swedish Chemicals Agency and the Swedish Medical Products Agency. The Agency for Marine and Water Management also periodically participated in project group meetings, and the Swedish Water and Wastewater Association provided ongoing input. A reference group associated with the commission also took part of the background material and conclusions. See Annex 2.

The work was conducted in projects at the Swedish EPA with an internal steering committee. The Agency for Marine and Water Management acted as co-opted members of the steering committee.

BACKGROUND MATERIAL

The commission focused on analysing the need for advanced treatment, the technological solutions available including their advantages and disadvantages, and other consequences of the use of advanced treatment. Two background reports developed within the framework of this commission (Wallberg et al., 2016, and Baresel et al., 2017) were used as the starting point for the analysis, as well as viewpoints from consultation stakeholders and the reference group.

An analysis of the need for advanced treatment of pharmaceutical residues and other hazardous substances based on the size of the WTP, receiving water type and risk of environmental effects has been conducted by Wallberg et al. (2016). The analysis includes discharge estimates for these substances and other hazardous substances from 14 WWTPs, as well as an estimate of the concentrations generated in the receiving waters. The data were obtained from the environmental monitoring⁶, Swedish EPA screening programme⁷ and other studies.

An analysis of the need for advanced treatment of pharmaceutical residues and other hazardous substances including their advantages and disadvantages, as well as the different levels of effectiveness, has been conducted by Baresel et al. (2017). The analysis is based mainly on research and experience from Sweden, but international studies have also been considered.

⁶The government-funded environmental monitoring is divided into ten different programme areas. Pollutant measurements are made within most programmes. Regarding pharmaceuticals, ten or so drug pharmaceutical substances are followed annually, including a few different antibiotics, in sludge and effluent from nine municipal WWTPs. For more information, see <http://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Miljoovervakning/Vad-ar-miljoovervakning/>

⁷ The screening subprogramme is part of the environmental monitoring programme Toxic Substances Coordination. This programme measured concentrations of a large number of pharmaceutical substances to obtain an overview of their distribution and presence in the environment. "Screening" refers to making inventories in order to identify emerging environmental contaminants that can cause problems to human health and the environment. For more information, see <http://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Miljoovervakning/Miljoovervakning/Miljogiftssamordning/Screening/>

This report also takes into account current research from the Agency for Marine and Water Management's ongoing work to promote advanced wastewater treatment, to the extent the research was available. In particular, results from the SystemLäk project ("Systems for the purification of pharmaceutical residues and other emerging substances") have been taken into account. The Agency for Marine and Water Management has received 32 million kronor in funding over a 4-year period (2014–2018) to promote advanced wastewater treatment with the aim to reduce discharges of pharmaceutical residues and other micropollutants that cannot be removed in the treatment plants' current processes.⁸ Eight projects have been awarded funding. Some projects have reported their results and others will report their findings in 2017 or 2018. A summary final report from the projects will be published in 2018. For more information about the different projects, see Annex 3.

⁸ Govt Bill 2013/14:1, State budget proposal for 2014, category 20.

3. Background

3.1. The challenges of pharmaceutical residues in wastewater treatment plants

For years, the Government has recognised the challenges of the adverse effects of certain pharmaceuticals in the environment. According to the Government's assessment, advanced technologies for the removal of pharmaceutical residues and other micropollutants should be tested and evaluated in full scale no later than 2018.⁹ Supplementing the WWTPs with advanced treatment methods could reduce discharges of pharmaceutical residues as well as other micropollutants that are not removed in a conventional wastewater treatment plant¹⁰. This investigation, as well as the ongoing investigation of the Agency for Marine and Water Management (see Annex 3), are part of these efforts.

The dominant flow of pharmaceuticals into the environment is through medication of humans. The drugs are excreted in urine or faeces and transported to the WWTPs and further to the receiving waters. Other sources of pharmaceutical residues in the environment include drugs used in veterinary medicine, fish farms and individual septic systems.

WWTPs are usually not designed to remove residues from pharmaceuticals or other hazardous substances, but are instead designed for wastewater treatment and removal of oxygen-consuming substances, phosphorus and nitrogen. Pharmaceutical residues with properties hazardous to the environment therefore pass largely unaffected through the WWTPs and reach the aquatic environment. A certain share also ends up in the sludge produced by these facilities.

Pharmaceuticals that have a physiological effect on humans may also have effects on animals and other living organisms. Harmful effects on wildlife have been observed both in the recipients outside the WWTPs and in laboratory studies. The release of active pharmaceutical ingredients into the environment can also contribute to the spread of antibiotic resistance.

Limiting the discharge of pharmaceutical residues into the environment requires a wide range of measures throughout the chain, from the development of new drugs, their manufacture and use through to the handling of residues and their release into the environment. Measures upstream of the WWTPs are still necessary, but are not sufficient for the foreseeable future to reduce the release of pharmaceutical residues from wastewater. Using advanced treatment technology at the WWTPs should be viewed as a complementary final step so that the wastewater is less polluted when the treated effluent reaches the receiving waters.

⁹ Govt Bill 2013/14:39, "Towards a toxin-free everyday environment – a platform for chemicals policy."

¹⁰ Govt Bill 2013/14:1, State budget proposal for 2014, category 20.

3.2. Wastewater treatment plants in Sweden

Approximately 85% of Sweden's population of about 10 million people are connected to roughly 1,700 municipal WWTPs, while others have individual (non-municipal) waste solutions (Swedish EPA and Statistics Sweden, 2016).

According to statistics from 2014, Sweden has 431 municipal WWTPs that are intended to serve more than 2,000 people or to receive wastewater with a pollutant load corresponding to more than 2,000 population equivalents (PE). The majority of the WWTPs are small ones. There are roughly 1,300 plants smaller than 2,000 PE that are not included in this commission. The group of 246 WWTPs in the size range 2,000–10,000 PE is classified as small in this report; see Table 1. There are 19 large WWTPs (larger than 100,000 PE) that treat approximately half of the country's wastewater volume. Of the 431 WWTPs, 135 are located at the coast. See Table 1 for more information.

This commission includes WWTPs greater than 2,000 PE and covers approximately 90% of the discharges from WWTPs in Sweden (Swedish EPA and Statistics Sweden, 2016).

Table 1. Number of municipal WWTPs in Sweden greater than 2,000 PE.
Source: Swedish EPA and Statistics Sweden (2016).

Size class [PE]		Number	of which are at the coast
Small*	2,001–10,000	246	65
Medium*	10,001–100,000	166	58
Large*	100,001–	19	12
<i>Total</i>		<i>431</i>	<i>135</i>

* Size according to this commission.

The locations of WWTPs greater than 2,000 PE are shown in Figure 1.

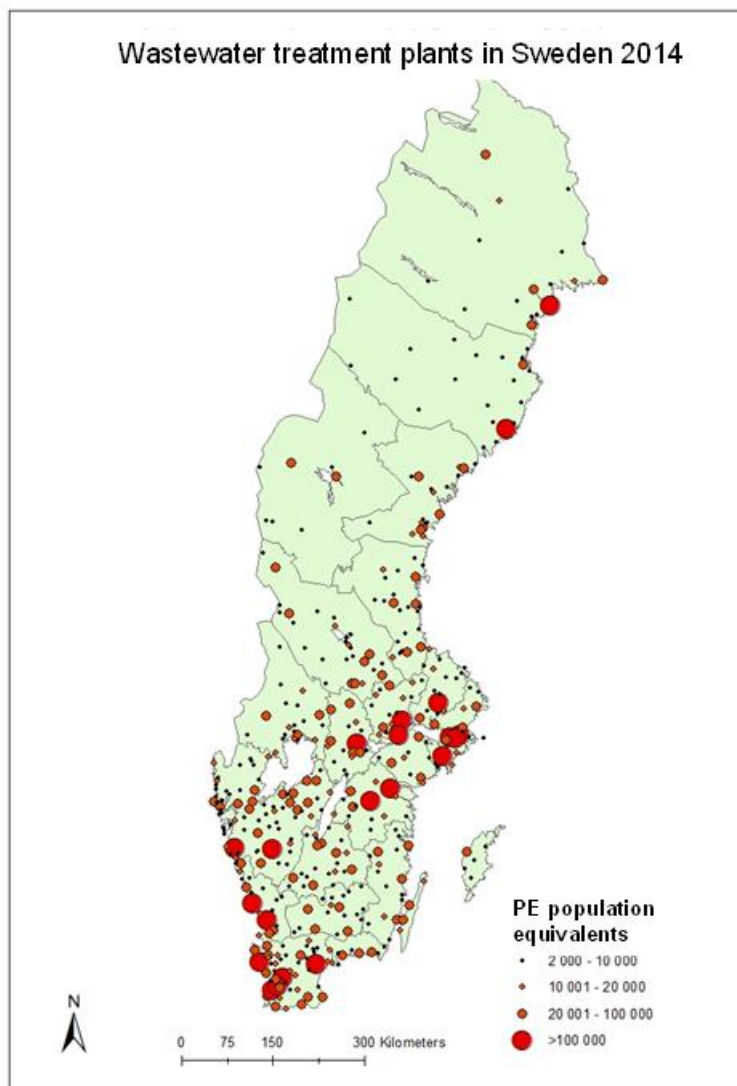


Figure 1. Location of WWTPs greater than 2,000 PE.
Source: Swedish Portal for Environmental Reporting (SMP).

A conventional WWTP consists of a combination of mechanical, chemical and biological treatments; see Figure 2.

Mechanical treatment is a pre-treatment step that separates solids such as toilet paper, cotton swabs, sand and gravel so that these fractions avoid entering the subsequent treatment steps.

During chemical treatment, flocculants (such as aluminium or iron) are added to remove phosphorus through chemical precipitation. The particles agglomerate and settle to the bottom, where they can be separated as sludge that is pumped to the sludge treatment of the WWTP. Chemical precipitation can be applied as pre-

precipitation during pre-sedimentation, simultaneous precipitation in the biological treatment or as post-precipitation.

During biological treatment, the wastewater is treated by microorganisms removing phosphorus, nitrogen and organic materials, often in a so-called activated sludge process in which microorganisms live in flocs that are held in suspension in the basin.

The sludge produced in the WWTP is separated and subsequently undergoes sludge treatment. The sludge treatment aims to stabilise the sludge prior to sludge dewatering. In Sweden the most common method of sludge stabilisation is anaerobic digestion, in which microorganisms degrade the organic material and produce biogas. Sludge dewatering then takes place in order to reduce the amount of sludge that is transported out of the WWTP. The reject water separated during dewatering is returned to the WWTP.

WWTPs in the north of Sweden do not use biological treatment to the same extent as in the rest of the country. Nor are there any general requirements for nitrogen removal, which is governed by regulations 2016:6 on the treatment and control of wastewater effluent from urban areas.

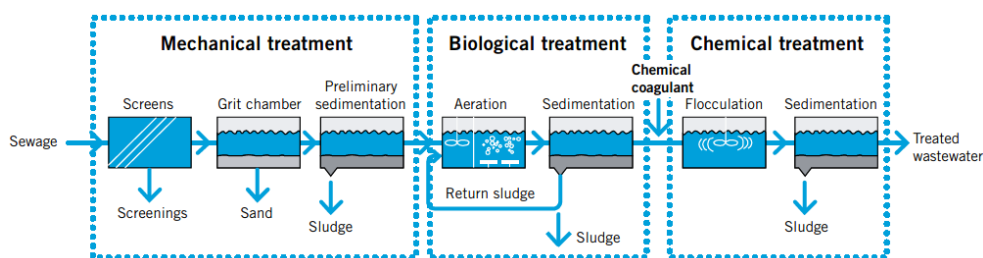


Figure 2. Treatment steps in a conventional WWTP. Source: Swedish EPA (2014).

4. The need for advanced treatment

This chapter contains an analysis of the potential need for advanced treatment of pharmaceutical residues at WWTPs in Sweden.

4.1. Pharmaceuticals released into the environment

WWTPs are currently not designed to remove pharmaceutical substances or other hazardous substances. To a certain extent, pharmaceutical substances are reduced using traditional wastewater treatment technology, mostly through biodegradation and adsorption to sludge particles.

WWTPs mainly discharge pharmaceuticals from human consumption. There are approximately 2,000 active pharmaceutical ingredients on the market for human medications. Pharmaceuticals that are not fully metabolised by the body are excreted via urination and excretion and then end up in our WWTPs. This is the absolute largest source of pharmaceuticals and pharmaceutical residues to the environment in Sweden. Other possible sources are emissions from hospitals and industry. A common misconception is that hospitals account for a large portion of the flow of pharmaceuticals into the environment. Based on defined daily doses, the sale of pharmaceuticals for inpatient treatment in Sweden constituted only slightly more than 2% of total sales in 2010, according to statistics from the pharmacy service Apotekens Service AB (Larsson and Löf, 2015). Even more advanced care now takes place in the home rather than in hospital.

Swedes are, from an international perspective, good at returning unused drugs. It is estimated that approximately 75% of unused drugs are returned. The rest end up mainly in household waste – which is usually incinerated in Sweden – and a smaller proportion is most likely flushed down the drain (Larsson and Löf, 2015).

In WWTPs, pharmaceutical substances meet three fates: either they are biodegraded, they end up in the treated wastewater effluent, or they end up in the sludge (Larsson and Löf, 2015). How well a drug biodegrades or is removed from the effluent partly depends on its chemical and physical properties (solubility, persistence) and partly on the WWTP process.

A summary of the removal efficiency of 62 pharmaceuticals in activated sludge plants with nitrogen treatment reveals that about 25% of the pharmaceuticals show a high degree of removal, 25% moderate, 25% low or no, and 25% show higher concentrations in the effluent than in the influent. The increase can be attributed mainly to the sampling methodology or the degradation of pharmaceuticals that have been conjugated¹¹. It is also difficult to take representative samples that reflect

¹¹ Conjugation means that the pharmaceutical is metabolised in the body so it can more easily be excreted. It can therefore not be detected in the influent. However, the conjugated pharmaceutical

influent and effluent at the same time; in addition, the influent is a complex matrix containing much organic matter (Hörsing, 2014).

The discharge volumes and concentrations of pharmaceutical residues that are discussed in this chapter (see section 4.5) are based on a sampling of the following pharmaceuticals (Wallberg et al., 2016):

Analgesic/anti-inflammatory

Diclofenac, ibuprofen, codeine, naproxen, paracetamol, ketoprofen, tramadol

Antimicrobial substances

Azithromycin, ciprofloxacin, erythromycin, fluconazole, ketoconazole, clarithromycin, norfloxacin

Cardiovascular agents

Eprosartan, flecainide, metoprolol

Neurological

Citalopram, carbamazepine, oxazepam, sertraline, zolpidem

Hormones

Levonorgestrel, estradiol, ethinyl estradiol

4.2. Environmental impact of pharmaceutical substances and other hazardous substances

Some of the pharmaceutical substances and other hazardous substances that reach the outside environment via WWTP effluent are persistent. The half-life can vary from one year to tens of thousands of years. Some persistent substances also bioaccumulate in living organisms.

The effects that then occur in aquatic environments are difficult to detect because everything takes place under the surface, which also makes it difficult to determine causation. The environmental impact of pharmaceuticals, alone or in combination with others, has not been studied. Yet it is clear that there are more and more studies on the environmental impact of pharmaceuticals, and likewise how long-term exposure to low concentrations can affect the environment.

Other hazardous substances that reach the environment through WWTPs also have environmental effects, alone or in combination with other hazardous substances (including pharmaceutical residues). Experience shows that, as new knowledge emerges, effects at lower concentrations are being discovered.

4.2.1. Pharmaceuticals

The purpose of active pharmaceutical ingredients is to provide a therapeutic effect. Therefore, they can also affect aquatic organisms whose enzymes, hormones and receptors are often similar to human ones (Gunnarsson et al., 2009). However,

then degrades in the WWTP to its original form, meaning that the effluent concentrations appear to be higher than in the influent.

there are many knowledge gaps concerning the effects of pharmaceuticals on the aquatic environment. Traditional testing of pharmaceuticals has mainly concentrated on acute toxicity, testing that is usually done on common industrial chemicals. Substances that affect reproduction or are acute toxic enough to lead to rapid death bring about such major ecological changes that we can actually see them in the environment. But pharmaceuticals are rarely acutely toxic, although exposure to low doses over a long period of time can have other effects, like behavioural changes, and require different testing methods. In other words, each drug can have its own particular impact.

The effects of pharmaceuticals in the environment have been long known. The first negative environmental effects that are partly attributable to pharmaceuticals were detected in English rivers by anglers in the early 1990's. The anglers were almost exclusively catching female fish, and many of the fish proved to be hermaphroditic. Several studies were initiated, and these revealed that young male fish held in cages downstream from English wastewater facilities began to produce vitellogenin, a protein normally found only in fertile females (Purdom et al., 1994). The effects were later linked to the treated wastewater's levels of natural human oestrogens and synthetic oestrogen, ethinyl estradiol, from birth control pills (Larsson et al., 1999). In experiments that exposed fish to treated wastewater, similar effects were found in Sweden (Adolfsson-Erici et al., 2005; Gunnarsson et al., 2009). Ethinyl estradiol can also have effects on the development of ovaries in amphibians (Pettersson and Berg, 2007).

Ethinyl estradiol has proved to be both more persistent and more potent than the natural oestrogens, meaning that lower levels are sufficient to produce an effect. Recently, pharmaceutical substances have also been found in otters (Roos et al., 2017).

Many laboratory studies have been conducted that demonstrate adverse effects in concentrations that are relevant to the external environment. For example, Zeilinger et al. (2009) showed that levonorgestrel, a progestin-like substance found in some birth control pills, had a major negative impact on the reproductive success of fish even at low levels. Fick et al. (2010) found that rainbow trout exposed to effluent from WWTPs in Stockholm and Umeå showed levels of levonorgestrel in their blood plasma that were higher than the human therapeutic dose. In addition, there are a variety of other pharmaceuticals that act through the same receptor as levonorgestrel, and it is likely that these pharmaceuticals have similar effects and can interact.

Triebkorn et al. (2004 and 2007) reported that diclofenac, carbamazepine and metoprolol can cause cell changes in several organs in rainbow trout at concentrations down to 1000 ng/L. De Lange et al. (2006) reported that the locomotion of the *Gammarus pulex* was affected at a concentration as low as 10 ng/L of fluoxetine and ibuprofen alone. Both fluoxetine (Brooks et al., 2005) and

ibuprofen (Brown et al., 2007) can be ingested and accumulate in aquatic organisms.

Behavioural changes resulting from exposure to antidepressants have also been reported in laboratory experiments in concentrations that are relevant in the receiving waters, such as the impact on the tendency of European perch to hide from predators (see, for example, Brodin, 2013). The behavioural impact, such as an altered search for food, is a highly relevant ecological effect but is not normally an effect included as an end point in a risk assessment (i.e., it is not an effect that is being investigated). Such changes can only be demonstrated by laboratory tests. But if concentrations in levels of a microgram or so per litre ($\mu\text{g/L}$) that cause these types of effects are present in the environment, this could have far-reaching consequences. Today, we lack sufficient knowledge to understand the significance of a species' potentially altered behaviour, for example close to a WWTP, for a population's well-being and survival.

If we take a look at studies of the marine environment, the effects of pharmaceuticals in the Baltic Sea are summarised by Hallgren and Wallberg (2015). The data collected show that the highest concentrations of pharmaceutical substances were found in blue mussels. A screening study from Norway found a large number of different pharmaceuticals in seabirds (Miljødirektoratet, 2013). This suggests that pharmaceuticals are passed on down the food chain. Not many studies are available on the effects of pharmaceuticals in the marine environment. But those that are available show that behaviours like locomotion and feeding are affected by the beta blocker propranolol for blue mussels, algae and crustaceans (Ericson et al., 2010; Eriksson Wiklund et al., 2011; Oskarsson et al., 2012; Oskarsson et al., 2014; Kumblad et al., 2015). Citalopram can affect the behaviour of fish by, for example, reducing their feeding behaviour (Kellner et al., 2015).

4.2.2. The spread of antibiotic resistance

The release of antibiotics into the environment can also contribute to the spread of antibiotic resistance. Resistant bacteria have been found downstream of municipal WWTPs (see, for example Larsson, 2012). There, the presence of resistant bacteria can be a result of intestinal bacteria that is already resistant having passed through these plants. The release of antibacterial substances from the facilities can also, in various ways, influence the spread of antibiotic resistance (see, for example, Sutterlin, 2015).

Research is underway to investigate in detail the spread of antimicrobial resistance via the environment at concentrations found in the receiving water body (Schmitt et al., 2017).

4.2.3. Other hazardous substances

It has been long known that chemical substances entering the environment can cause injury and accumulate in living organisms. The impact of DDT¹² and PCBs¹³ on seals, eagles and other birds and animals are some examples of this (Bernes, 1998). The effects of metals and organic contaminants in aquatic environments have also been demonstrated by the Swedish EPA (2008).

It is often difficult to pinpoint a single environmental pollutant as the cause of the observed effects. A contributing factor could be mixtures of a large number of potentially toxic substances that together result in the effects recorded. For traditional organic environmental contaminants like DDT and PCBs, as for other halogenated organic compounds, substantial declines in concentrations in biota have been observed since the 1970's. However, there are increasing levels of other, newer substances, like brominated flame retardant and highly fluorinated compounds (PFASs).

4.3. Factors that influence the concentrations in receiving waters

The probability of high pharmaceutical concentrations close to the receiving waters depends on the amounts released, the drug's properties, such as persistence and bioaccumulation, and the water recharge rate in the receiving water body. Receiving waters with a high water recharge rate relative to flow from the WWTPs can receive higher amounts of pollutants without exceeding the effect levels in the receiving waters. However, the exact concentration levels of many pharmaceuticals in waterways is not always known.¹⁴

4.3.1. Amounts and properties of released pharmaceuticals

Large WWTPs can have a greater impact than smaller WWTPs because they release large amounts of pollutants. Dilution calculations suggest that pharmaceuticals discharged from WWTPs in marine coastal areas spread quickly under the detection limit (Wallberg et al., 2016). Thus, one could expect that pharmaceuticals are rarely detected in samples of sea water, but this is not the case. A recent review of data from countries around the Baltic Sea notes that pharmaceuticals are often detected even in sea water samples (Hallgren and Wallberg, 2015). Some medications can also bioaccumulate and can be found in marine animals like mussels, fish and seabirds.

¹² Dichlorodiphenyltrichloroethane

¹³ Polychlorinated biphenyls

¹⁴ The government-funded environmental monitoring does not conduct continuous measurements of the pharmaceuticals in waterways. Instead, it takes annual measurements of about a dozen substances (including a few different antibiotics) in sludge and effluent from nine municipal WWTPs. For more information, see <http://www.naturvardsverket.se/Miljoarbete-i-samhallet/Miljoarbete-i-Sverige/Miljoovervakning/Vad-ar-miljoovervakning/>

As for the release of primarily persistent substances, the amount released is an important factor since the substances will accumulate and persist in the environment for a long time to come. So, even if no effect levels¹⁵ will be exceeded initially, concentrations will increase over time, which can lead to exceeded effect levels over time. This is an important factor for water bodies like the Baltic Sea, which has a sensitive ecosystem, a low water recharge rate and receives sewage water from millions of people. Half-lives for the persistent substances that are currently released into the environment vary from one year to tens of thousands of years. A constant discharge of more easily degradable substances can also have an impact, because even if the levels are low the exposure is constant.

The amount of pharmaceutical substances and other hazardous substances discharged from a WWTP depend on the number of people served by the facility but also on the industries connected and the presence of urban runoff water. With regard to the number of people connected, we should also take into account that the amount can vary significantly over the year in some areas due to the high percentage of holiday homes.

Estimated quantities of pharmaceuticals that are released annually from a selection of WWTPs are listed in Annex 4 (Wallberg et al., 2016). In the effluent from some WWTPs all the selected substances are found, while in other cases smaller quantities are found. The effluent concentrations vary from a few nanograms per litre to a few micrograms per litre. The total quantities discharged from WWTPs vary from a few grams to several hundred kilograms per year, depending on the substance and the type and size of the WWTP.

Table 2 (section 4.5.1) contains examples of the concentrations in receiving waters for three selected WWTPs.

4.3.2. Several WWTPs within the same catchment area

If multiple WWTPs are located within the same catchment area, then additional pharmaceutical substances and other hazardous substances are released downstream, which means that the impact zone gets bigger. Between 41 and 65 WWTPs are located within the catchment area in Sweden that has the greatest number of WWTPs within the same catchment area. Several WWTPs can also discharge into some of the larger lakes.

4.3.3. Water recharge rate in the receiving waters

In this context, the receiving waters can be divided into three categories (Wallberg et al., 2016):

- Receiving waters with large initial dilution
- Receiving waters with varying conditions
- Receiving waters with little or no initial dilution

¹⁵ See also section 4.5.1.

RECEIVING WATERS WITH LARGE INITIAL DILUTION

For receiving waters with a high water recharge rate or large flow relative to the WWTP effluent, the dilution will be large or very large. This is the case, for example, when the effluent is discharged into or near the sea.

RECEIVING WATERS WITH VARYING CONDITIONS

In the immediate area outside a WWTP that discharges its treated wastewater into rivers, bays or lakes with limited water recharge, there is a greater risk that concentrations will exceed the effect levels during the summer months at low water flow or depending on the water levels in a lake.

RECEIVING WATERS WITH LITTLE OR NO INITIAL DILUTION

The dilution area with concentrations above effect levels will, especially at low water flows, likely extend several kilometres downstream of the point of discharge into the receiving waters with little or no initial dilution.

4.4. Sensitivity of receiving waters to pharmaceutical residues

The receiving waters' sensitivity to pharmaceutical residues, such as ecological sensitivity and the potential risk of contamination of drinking-water supplies, is a significant factor in the need for advanced treatment.

4.4.1. Ecological sensitivity

Receiving waters with spawning fish, amphibians and other aquatic organisms are particularly susceptible to exposure to hazardous substances. Knowledge about the location of spawning and nursery areas for fish, both in freshwater and salt water, is generally flawed. In marine areas, these areas are often found along the coast. In freshwater areas, fish can live in virtually all types of receiving waters, provided that there are no water hazards, even in small dikes. Fish spawn in vegetation-rich shallow areas at different times depending on the species for much of the year, but especially in spring and autumn. Another factor that affects their sensitivity is whether the receiving waters are home to red-listed species or are near Natura 2000 areas.

The Baltic Sea is a sensitive ecosystem with low salinity, low biological diversity and few trophic levels. This means that the ecosystem is more sensitive to dangerous substances than other marine areas (havet.nu, 2017). Wastewater effluent is discharged into the Baltic Sea from millions of people, and the residence time for the sea water – and thus for persistent substances like the drug diclofenac – is long.

4.4.2. Drinking water

Half of all water used for drinking water in Sweden comes from surface waters such as lakes, rivers or streams (Swedish Water & Wastewater Association, 2017). One example is Lake Mälaren, which supplies about 2 million people with drinking water and at the same time acts as a receiving water body for several WWTPs.

Threshold values are available as quality criteria for good drinking water. To demonstrate that the criteria are met, drinking water manufacturers examine the drinking water regularly in order to detect the presence of hazardous substances such as bacteria and other microorganisms. Thresholds are available for metals, pesticides, aromatic hydrocarbons and PFASs (highly fluorinated substances), but not for pharmaceutical substances.

The World Health Organization has noted that surveys of pharmaceutical residues in drinking water all indicate that the levels are several orders of magnitude (more than 1,000 times) below the lowest therapeutic dose and far below the acceptable daily intake. Large safety margins for individual substances indicate that significant adverse effects on human health are highly unlikely at current exposure levels for pharmaceutical substances in drinking water (WHO, 2012).

4.5. Concentrations in the surrounding environment due to discharges

4.5.1. Pharmaceutical residues

The amounts of pharmaceutical substances discharged from WWTPs vary from plant to plant. Depending on flows and dilution, this leads to different concentrations in the receiving waters.

The impact of pharmaceutical concentration levels on the environment can be assessed using criteria for particular pollutants or effect levels. At present, there are assessment criteria for inland and coastal waters for three drugs in Sweden: diclofenac, estradiol and ethinyl estradiol. These are listed as river-basin-specific pollutants under the regulations of the Agency for Marine and Water Management (2013:19) on classification and environmental quality standards with respect to surface waters. If these pollutants are released in significant amounts¹⁶ to a specific body of water, the criteria should be used to assess whether the substances are present in concentrations that would jeopardize achieving the environmental quality standard for good ecological status of the water body or would worsen the status. The environmental quality standards are applicable to permitting and oversight. See also section 6.1.1.

¹⁶ A significant amount means an amount that poses a risk of adversely affecting the ecological status. If there is a risk that the environmental quality standard is exceeded, this implies a significant amount.

In addition to this, effect levels for adverse effects in the environment¹⁷ are presented in the scientific literature. Generally, the uncertainties are great around the effect levels available for pharmaceuticals, and this should be kept in mind for any risk assessments. For more information, see Wallberg et al. (2016, Chapter 5).

A constant flow even of low concentrations can affect organisms when they are exposed to these substances and over an extensive period time. Combination effects are also an important consideration, since mixtures of pharmaceutical substances and other hazardous substances can produce an ecotoxic effect even if the individual substances are present in such low concentrations that they do not have any impact individually. Analgesics such as diclofenac, ibuprofen, naproxen and acetyl salicylic acid in combination have been shown to have effects at much lower concentrations than in experiments with individual substances. Combination effects have also been reported for other pharmaceuticals that can be assumed to have the same mode of action, including antibiotics, antidepressants, beta-blockers, and pharmaceuticals in combination with other chemical substances (summarised by Backhaus, 2014, for example).

In one study, concentrations of pharmaceutical residues in receiving waters downstream of the WWTPs were calculated for a selection of Swedish WWTPs. The calculated levels in the receiving waters exceed assessment criteria values and effect levels for several pharmaceuticals and WWTPs (Wallberg et al., 2016). Table 2 contains examples of the concentrations in receiving waters for three selected WWTPs with low, variable and high initial dilution in the receiving waters. The pain relievers diclofenac and ibuprofen, the cardiovascular substance metoprolol, and the hormones ethinyl estradiol, estradiol and levonorgestrel are present at levels that exceed the values in the assessment criteria or effect levels in the immediate area outside the Swedish WWTPs, according to calculations made by Wallberg et al. (2016). For the three pharmaceuticals listed as especially polluting substances, the assessment criteria values are exceeded in the receiving waters for all three substances at several of the WWTPs. The table also shows the number of WWTPs with effluent that exceeds the assessment criteria values or effect levels according to the number of WWTPs surveyed. In the table, the measured maximum concentrations in the effluent are used together with the minimum dilution factor for each WWTP, but exceedances are noted even when using mean concentrations and mean dilution. This indicates that there is a need to further investigate whether such receiving waters meet the requirements for good ecological status.

Annex 4 contains a summary of the substances analysed at each plant as well as the quantities (calculated at the mean concentration) discharged per year (kg/year) in the study conducted by Wallberg et al. (2016).

¹⁷ Effect levels are water concentrations at which the pharmaceuticals could impact the environment.

Table 2. Estimated concentrations (ng/L) of pharmaceutical substances in receiving waters for the three selected WWTPs, and number of WWTPs exceeding the criteria values or effect level values in relation to the number of surveyed WWTPs.
Source: Wallberg et al. (2016).

Substance	Max. concentration in receiving waters (ng/L) when using the minimum dilution factor			Number of WWTPs with effluent exceeding the values in assessment criteria or effect level per number of surveyed WWTPs
	WWTP with small initial dilution	WWTP with variable conditions	WWTP with large initial dilution	
Hormones				
Ethinyl estradiol	1	0.07	0.04	4/6
Estradiol	1	0.07	0.009	2/6
Levonorgestrel	1	0.3	0.04	9/13
Antimicrobial				
Azithromycin	6	0.4	0.03	0/7
Ciprofloxacin	6	3	0.1	0/14
Clarithromycin	19	2	1	0/7
Erythromycin	56	3	0.9	0/7
Fluconazole	132	3	2	0/8
Ketoconazole	30	0.4	0.04	0/7
Norfloxacin	1	0.07	0.009	0/14
Neurological				
Citalopram	89	4	0.9	0/7
Carbamazepine	278	9	2	0/9
Oxazepam	185	7	0.8	0/7
Sertraline	8	0.4	0.06	0/9
Zolpidem	10	0.3	0.03	0/7
Analgesic				
Diclofenac	987	14	2	5/14
Ibuprofen	35	14	2	1/14
Ketoprofen	43	4	0.5	0/14
Codeine	152	2	1	0/7
Naproxen	33	3	0.9	0/14
Paracetamol	104	8	0.4	0/7
Tramadol	709	21	5	0/7
Cardiovascular				
Eprosartan	25	5	2	0/7
Flecainide	58	2	0.2	0/7
Metoprolol	506	21	5	3/7

Red highlighting means the values exceed the criteria. Orange highlighting means the values exceed the effect level.

*Estimated maximum concentrations at mean dilution factor in receiving waters have been used.

As a comparison with the measured concentrations, the calculated levels of diclofenac in Fyrisån (Wallberg et al., 2016) correspond relatively well to the concentrations previously measured in Fyrisån, and the assessment criteria value is exceeded in both cases. In a screening study conducted on behalf of the Swedish

EPA, 101 pharmaceuticals were measured in influent and effluent waters from WWTPs, sludge, surface water, drinking water and biota. Of the studied pharmaceuticals, 91% were detected in the influent, 84% in the effluent, 72% in the sludge, 65% in the surface water, 23% in the biota and 26% in the drinking water. Fifteen of the 101 pharmaceuticals were detected in concentrations so high that they are expected to have a pharmacological effect in fish (Fick et al., 2014).

4.5.2. Other hazardous substances

Corresponding calculations of discharges and concentrations in receiving waters were also made for about fifty other hazardous substances (Wallberg et al., 2016). These substances can be divided into five groups: fluorinated substances, chlorophenols/phenols, musks, organophosphates and organotins. Threshold values are not available for most of these substances but effect levels are described in the scientific literature, although the uncertainty around these values is generally quite high. For the substances investigated, the assessment criteria value was exceeded for PFOS¹⁸ (fluorinated substances) in freshwater/coastal water in four out of nine WWTPs surveyed. It should be noted that there are 3,000 highly fluorinated substances (PFAS) commercially available on the world market (Swedish Chemicals Agency, 2015) for which there are no thresholds. These substances are extremely persistent in the environment, and several of them accumulate easily in living creatures (bioaccumulative) and are toxic.

Persistent substances in general, along with metals, also risk accumulating over time and so their release should be avoided.

4.6. The need for advanced treatment

The Swedish EPA estimates that there is a need for advanced treatment in at least some of the WWTPs based on the discharge of pharmaceutical residues. The release of other hazardous substances and the risk of contributing to the spread of antibiotic resistance reinforce this need. The need varies based on concentrations in the receiving waters and their sensitivity. Values exceeding those from the assessment criteria and effect levels occur. The question of how many WWTPs require advanced treatment cannot be determined with existing evidence. However, the Swedish EPA has identified important factors for prioritising the necessary actions.

Improved treatment that aims to eliminate pharmaceutical residues from wastewater can also have other positive effects. This is because many of the chemicals we use in our lives also reach the external environment through WWTPs. Improved treatment will also reduce the dispersion of these hazardous substances into the environment. And finally, improved treatment can also reduce

¹⁸ Perfluorooctane sulphonate (PFOS), included in PFAS

the spread of bacteria that carry antibiotic-resistant genes and other substances that could affect the spread of antibiotic resistance.

The probability of high pharmaceutical concentrations close to the receiving waters depends on the amounts discharged and the water recharge rate in the receiving waters. Receiving waters with a high water recharge rate relative to flow from the WWTPs can receive higher amounts of pollutants without exceeding the effect levels in the receiving waters compared with a receiving water body with a low recharge rate.

As for the discharge of primarily persistent substances, the amount discharged is an important factor since the substances will accumulate and persist in the environment long into the future. So, even if no effect levels are exceeded initially, concentrations will increase over time.

At present, there are few water thresholds for either pharmaceuticals or other hazardous substances. The scientific literature provides effect levels that can be used to compare the concentrations of pharmaceutical substances and other hazardous substances found in the environment. The uncertainties surrounding the effect levels, however, are great. Calculated concentrations for several pharmaceuticals in the receiving waters of most WWTPs examined in the initial report (Wallberg, et al., 2016) exceeded the values in the assessment criteria and effect levels.

The conclusion is that there is a need for advanced treatment, and that some receiving waters are affected more than others by residue discharges due to local factors. These circumstances must be taken into account when determining priorities for which WWTPs need to introduce advanced treatment and where to begin.

- WWTPs with receiving waters that have a low water recharge rate, meaning that the concentrations in the surrounding area often risk exceeding effect concentrations.
- WWTPs that discharge to sensitive waters with effluent from several plants or whose effluent from large WWTPs has an environmental impact, which can lead to concentrations that risk exceeding effect concentrations.
- WWTPs that release large amounts of pharmaceuticals and hazardous substances, regardless of receiving waters, since the discharge of mainly persistent substances will accumulate in the environment over a long period of time.
- WWTPs with sensitive receiving waters, such as waters that are home to red-listed species, that supply (or are planned to supply) drinking water or that are near Natura 2000 areas.

5. Technological solutions

This chapter describes the technologies that can be used for advanced treatment, with a short description of their function and the advantages and disadvantages of each with regard to removal efficiency, operation, economy, environment, residues and occupational health and safety. The capital expenditures (CAPEX) and operating expenses (OPEX) for these technologies are presented in more detail in section 6.4. A more detailed description of the advantages and disadvantages of the technologies are available in Annex 5 and in Baresel et al. (2017).

5.1. Available technologies

Several technologies are currently available for the advanced treatment of pharmaceutical residues and other hazardous substances. Figure 3 shows an overview of them. The technologies can be divided into four different treatment methods: physical, oxidative, biological and adsorptive. They can also be combined for an optimised treatment of micropollutants.

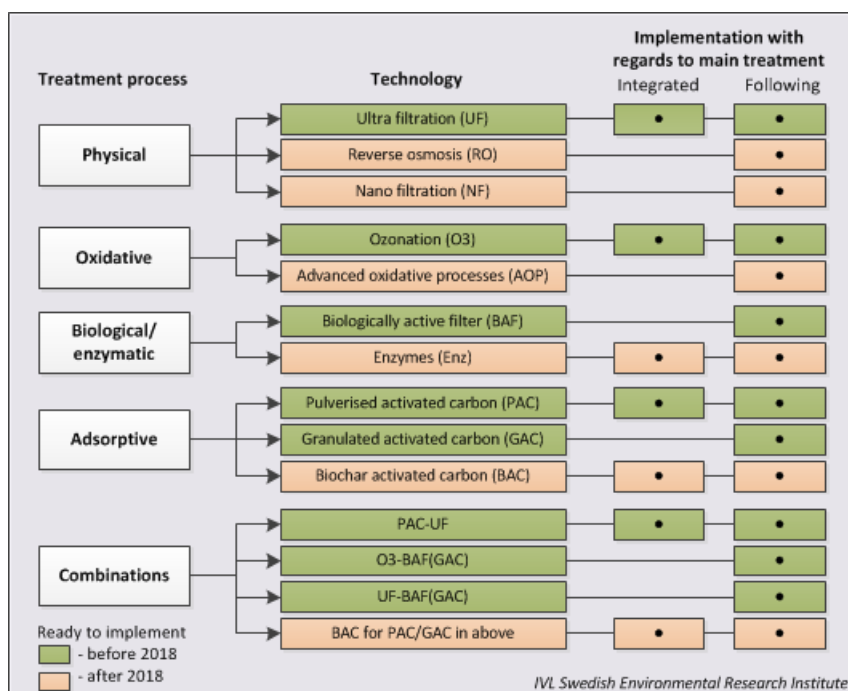


Figure 3. Schematic characterisation of different additional treatment technologies.
Source: Baresel et al. (2017).

The following sections describe only those technologies that are sufficiently accessible and realistic to implement today. Subsequent sections then describe technologies that are considered to be under development.

5.1.1. Ozonation (O₃)

Ozonation (O₃) is an oxidative treatment in which different substances are oxidized with ozone. The most common application for the degradation of organic micropollutants is as a final polishing step following the main treatment process or integrated into the main treatment process. The degradation rate of persistent organic compounds depends on factors like ozone dose and contact time, but is also influenced by the concentrations of other organic compounds in the treated effluent.

One advantage of ozonation is that it is a versatile technology that provides the capability to control ozone doses. Also, the same removal efficiency can be expected over the lifetime of the treatment plant. Ozonation requires active monitoring and control to obtain an optimised process, and the technologies for this are under development. A disadvantage of ozonation is the formation of by-product residues that can have ecotoxicological effects. This technology therefore requires post-treatment in order to minimise the risks of degradation products. Furthermore, the energy consumption is relatively high.

A WWTP was put into operation at Tekniska Verken in Linköping in 2017, which will provide us with valuable experience.

5.1.2. Granular activated carbon (GAC)

The basic principle of granulated activated carbon (GAC) is the adsorption of contaminants on the active carbon surface. When GAC is used, the carbon is placed in filter beds in a separate treatment step. When the carbon has become saturated (adsorption surfaces are unavailable), it needs to be replaced by new carbon in order to maintain the removal efficiency. The spent carbon is regenerated and can then be used again.

This technology has been used for a long time in various water treatment applications, and exhibits a good removal efficiency for pharmaceutical residues. Obtaining an effective treatment requires minimising the pollutant level and the concentration of suspended solids in the water to be treated. This method has relatively low energy consumption during operation, but has high resource consumption during the production and regeneration of the activated carbon. Activated carbon based on different biosubstrates is currently being developed; see section 5.1.9.

5.1.3. Powdered activated carbon (PAC)

Treatment with activated carbon can also be done using powdered activated carbon (PAC). This treatment process is also based on adsorption of contaminants on the carbon, where the carbon is added to the main treatment process in the biological stage before any final filtering in a sand filter or in an additional treatment step. Unlike GAC, PAC is separated with the sludge if it is added to the main treatment process and thus not regenerated.

One advantage of PAC is that it only requires the installation of storage and dosing equipment when it is being added to the main treatment process. Also, the dosage can be adjusted for the influent load. In certain applications the PAC dosage can lead to contamination of the sewage sludge, which limits the possibilities of using it as fertiliser on farmland.

5.1.4. Ultrafiltration (UF)

Ultrafiltration (UF) is a physical treatment method that uses a membrane to filter particles. Depending on the membrane selection, particles and even larger soluble molecules can be separated down to about 10 nm. UF integrated in the main treatment at a WWTP as a membrane bioreactor (MBR) is available in full scale, but UF is more unusual as a separate, subsequent treatment step. UF is also used as a microbiological barrier for treating drinking water.

One advantage of ultrafiltration technology is that it acts as a physical barrier to the receiving waters and for any subsequent treatment steps to separate pharmaceutical residues (ozonation or activated carbon). It has a good treatment effect on particulate matter, microplastics, pathogens and bacteria and thus also on multi-resistant bacteria, but not on the resistance formation in general. A drawback to this technology is that it does not remove substances that are soluble in the aqueous phase, which is why most pharmaceutical residues are not separated using UF. The technology requires the use of chemicals and increased energy consumption. Furthermore, the technology is considered to be generally more expensive than other technologies. But as advancements in membrane production take place, costs continue to decline.

5.1.5. Biologically active filtration (BAF)

Biologically active filtration (BAF) uses standard filters (such as sand filters or activated carbon) which, in addition to the filtering effect, also involve biological activity that breaks down certain pollutants.

One advantage of this technology is that it is based on traditional sand filters or GAC systems, which are established technologies at WWTPs. GAC as a filter media is advantageous because it provides adsorption of pollutants and a high specific surface area where microorganisms attach and pharmaceutical residues can be removed. Many micropollutants are degraded either in a biofilm system or an activated sludge system, which is why BAF with activated carbon offers the highest removal efficiency.

5.1.6. The combination of powdered activated carbon and ultrafiltration (PAC-UF)

The combination of powdered activated carbon (PAC) and ultrafiltration (UF) can be used as an integrated or additional treatment step at existing WWTPs. The

integrated treatment consists of an MBR process in which PAC is added to the MBR reactor.

A combination of PAC and UF meets the requirements of an effective separation system with activated carbon that removes pollutants through adsorption, and ultrafiltration that separates and removes all pollutants larger than the membrane's pore diameter, including any residues of contaminated powdered activated carbon. One disadvantage of using activated carbon in powder form is that it hinders the regeneration of the activated carbon. Using PAC-UF as a separate treatment step following main treatment requires separate handling of the resulting sludge (retentate) if it is not to affect the quality of the sludge produced at the WWTP. If, instead, PAC is added to an MBR reactor integrated in the treatment process, the existing sludge management will have a negative impact on the sludge quality as a result.

5.1.7. The combination of ozonation and biologically active filtration (with granulated activated carbon)

This technology combination consists of ozonation and biological post-polishing with granulated activated carbon (GAC) as a filter material. It provides a multi-step treatment using both oxidative and biological degradation as well as adsorption of pollutants and by-products formed during ozonation. The ozonation step provides dynamic control of the removal efficiency. This technology combination has been tested both with and without microfiltration as a pre-treatment prior to ozonation (Baresel et al., 2017), and provides a nearly complete removal of pharmaceutical residues and other hazardous substances, except for microplastics.

5.1.8. The combination of ultrafiltration and biologically active filtration (with granulated activated carbon)

This system combines membrane separation with a biological and adsorptive filter. The membrane can be integrated in the WWTP. In this case, the system is called a membrane bioreactor (MBR) with subsequent biological and adsorptive filtration (BAF (GAC)).

Because the activated carbon is not added to the membrane stage, this reduces the load on the membrane and helps avoid a negative impact on the sludge quality compared with the powdered activated carbon (PAC) system. The removal efficiency of BAF is determined entirely by the biology and adsorption capability of the filter material. The technology combination of UF (which removes microplastics and multidrug-resistant bacteria) and activated carbon (which removes pharmaceutical residues, including antibiotics) can prevent a possible multidrug resistance downstream of the WWTP (Baresel et al., 2017).

5.1.9. Examples of technologies under development

This section describes several technologies that are considered to be under development. They are available today mainly in pilot scale. How quickly they can

be implemented depends on several factors, such as treatment results on a larger scale and competitiveness with regard to investment and operational costs. External factors, such as the need to recycle wastewater, may also be relevant.

REVERSE OSMOSIS/NANOFILTRATION

This technology requires a smaller nominal pore size than ultrafiltration (0.001-0.01 μm). Its use often requires pre-treatment with UF for more resource-efficient operation and manageable maintenance. Extensive treatment can be achieved, but not for all substances (for example, not for diclofenac). In addition, a concentrate is formed that requires treatment with, for example, ozone or GAC, which means that the membrane stage does not have any real justification in respect of the removal of pharmaceutical residues (Baresel et al., 2017). The technology can be applied when a reuse of the treated wastewater is desirable.

ADVANCED OXIDATION PROCESSES (AOP)

These processes include advanced oxidative treatment with agents such as UV or titanium dioxide (TiO_2) in combination with ozone. The technology requires relatively particle-free water and separate reactor volumes. The conclusion from IVL's survey of previous studies is that some pharmaceutical substances can be mineralised completely using AOP, whereas others are considerably more resistant and more difficult to remove (Baresel et al., 2017). AOP shows potential as an additional treatment technology when high drug concentrations are present or when other technologies are insufficient (Baresel et al., 2017).

BIOLOGICAL ACTIVATED CARBON (BAC)

The development of activated carbon will be able to provide a more resource-efficient treatment with GAC/BAF and PAC. Because 10-20% of the activated carbon is consumed at regeneration, it is interesting to find materials of non-fossil origin, such as the production of sewage sludge biochar from WWTPs. This process is under development and requires continued research and development efforts. In the SystemLäk project (see Annex 3), adsorption tests conducted with different types of biochar demonstrated that some could reduce pharmaceutical residues in the tested effluent with a capacity comparable to that of commercially available activated carbon (Baresel et al., 2017).

5.2. Overall assessment of removal efficiency

Pharmaceutical residues reach the treatment facilities primarily as metabolites, which are formed in the human body and excreted via urine and faeces. A recent Swedish study (Hörsing et al., 2014) shows that about 25% of pharmaceutical residues are removed in WWTPs, and the total concentration of an additional 25% is reduced but not removed completely from the aqueous phase. Here, 'removal' means that the substances are removed from the aqueous phase either through degradation or through transfer to the sludge phase. The other 50% are not

considered to be removed without additional or improved treatment methods (Baresel et al., 2017).

Table 3 presents an assessment matrix for the treatment of pharmaceutical residues (Baresel et al., 2017). Removal efficiency is assessed in four categories: none, low, moderate or good removal efficiency.

Baresel et al. (2017) describe each drug in more detail. For certain pollutants included in the survey, there is no information about the removal efficiency for some or all of the treatment technologies. If the biochemical and physical properties of these pollutants permit the assessment of expected removal efficiency, this is indicated below in Table 3. The assessment of the expected removal efficiency includes properties such as the number of unsaturated bonds, halogen content (chlorine, fluorine, bromine, etc.), density, texture, polarity and solubility.

As can be seen from the table, combinations of different technologies that use various treatment mechanisms – physical processes, oxidative methods, biological methods and adsorption – result in a nearly complete removal of all pharmaceutical substances from the wastewater. Ultrafiltration (UF/MBR) treats only particulate fractions, which means that it does not have a treatment effect on pharmaceutical residues that are soluble in the aqueous phase.

Table 3. Assessment matrix – technological solutions for the treatment and removal of pharmaceuticals. Source: Baresel et al. (2017).

Pharmaceutical	Treatment technology/combination							
	UF ¹	GAC	PAC ²	BAF ³	O ₃ ⁴	PAC-UF	O ₃ -BAF (GAC)	UF-BAF (GAC)
Azithromycin	-	(+++)	+++	+++	+	+++	+++	+++
Ciprofloxacin	-	+++	+++	+++	++	+++	+++	+++
Clarithromycin	-	(+++)	(+++)	(+++)	(+)	(+++)	(+++)	(+++)
Diclofenac	-	+++	+++	+++	+++	+++	+++	+++
E2 (17β-estradiol)	-	+++	+++	+++	+++	+++	(+++)	+++
EE2 (17α-ethinyl estradiol)	-	+++	+++	+++	+++	+++	(+++)	+++
Erythromycin	-	(+++)	(+++)	(+++)	(+)	(+++)	(+++)	(+++)
Ibuprofen	-	+++	+++	+++	++	+++	+++	+++
Carbamazepine	-	+++	+++	+++	+++	+++	+++	+++
Levonorgestrel	-	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)
Metoprolol	-	+++	+++	+++	+++	+++	+++	+++
Oxazepam	-	+++	+++	+++	++	+++	+++	+++
Propranolol	-	+++	+++	+++	(+++)	+++	+++	+++
Sertraline	-	+++	+	+++	++	+	+++	+++
Sulfamethoxazole	-	+++	+++	+++	+++	+++	+++	+++
Trimethoprim	-	+++	(++)	+++	+++	(++)	+++	+++

- = No treatment; + = 0-<20%; ++ = 20-<80%; +++ = >80% removal efficiency; () = Expected efficiency based on the substance's properties and the technology's treatment mechanism.

UF = ultrafiltration; GAC = granular activated carbon; PAC = powdered activated carbon; BAF = biologically active filtration; O₃ = ozonation; PAC-UF = the combination of PAC and UF; O₃-BAF(GAC) = the combination of O₃ and BAF with GAC as filter material; UF-BAF(GAC) = the combination of UF and BAF with GAC as filter material.

¹ Some separation can occur for substances that are attached to particles ² Assumes effective separation of PAC

³ Using GAC as filter material

⁴ For an ozone dose of 0.5-1 mg O₃/g DOC

Table 4 presents the removal efficiency for other pollutants. The combination of technologies provides a more extensive treatment for more substances than any one technology alone. UF/MBR achieves good removal efficiency for pathogens and bacteria, and thereby also for antibiotics (VRE). Except for nonylphenol, bisphenol A and oestrogen effects (YES), which are more effectively removed via ozonation, adsorptive/biological treatment technologies have a slightly higher removal efficiency for many pollutants (Baresel et al., 2017).

Table 4. Assessment matrix – technical solutions for the treatment of *other substances* or risk of increased incidence of different effects

Source: Baresel et al. (2017).

Effect/pollutant	Treatment technology/combination							
	UF	GAC	PAC	BAF	O ₃	PAC-UF	O ₃ -BAF (GAC)	UF-BAF (GAC)
Antibiotic resistance (VRE)	++	+	+	+	+	+++	++	+++
Risk of infection	+++	+	-	+	++	+++	++	+++
Bisphenol A	-	+	+	+	+++	+	+++	+
Cybutryne/Irgarol	-	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)
Dioxins ¹ (PCB-28 to PCB-189)	-	(+++)	(+++)	(+++)	(++)	(+++)	(+++)	(+++)
Endotoxins	-	(+++)	(+++)	(+++)	(+)	(+++)	(+++)	(+++)
Estrogenic effects (YES)	-	-	(-)	-	+++	(-)	+++	(-)
Phthalates (e.g., DEHP)	-	+++	+++	+++	+	+++	+++	+++
Flame retardants (e.g., HBCD)	-	+++	+++	+++	+	+++	+++	+++
Chloroalkanes (C10 to C13) ¹	-	(+++)	(+++)	(+++)	(+)	(+++)	(+++)	(+++)
Linear alkylate sulfonates (LAS) (C10 to C13)	-	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)
Nonylphenol	-	+	+	+	++	+	++	+
Octylphenol	-	+++	+++	+++	++	+++	+++	+++
PFAS (incl. PFOS)	-	+++	+++	+++	+	+++	+++	+++
Sucralose	-	+++	+++	+++	+	+++	+++	+++
Terbutryn	-	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)	(+++)
Tributyltin (TBT) ¹	-	(+++)	(+++)	(+++)	(+)	(+++)	(+++)	(+++)
Trichlorobenzene ¹	-	(+++)	(+++)	(+++)	(++)	(+++)	(+++)	(+++)
Triclosan	-	+++	+++	+++	++	+++	+++	+++
Heavy metals ²	(+)	(+)	(+)	(+)	-	(+)	(+)	(+)
Avoids harmful degradation products	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

- = No treatment; + = 0-20%; ++ = 20-70%; +++ = >70% treatment effect; () = Expected efficiency based on the substance's properties and the technology's treatment mechanism).

UF = ultrafiltration; GAC = granular activated carbon; PAC = powdered activated carbon; BAF = biologically active filtration; O₃ = ozonation; PAC-UF = the combination of PAC and UF; O₃-BAF(GAC) = the combination of O₃ and BAF with GAC as filter

material; UF-BAF(GAC) = the combination of UF and BAF with GAC as filter material.

¹ Ends up mainly in the sludge phase.

² Expected effect is based on a few measurement results for individual metals and treatment mechanism.

5.3. Overall assessment of operational considerations

Table 5 presents a summary of the facility and operational considerations (Baresel et al., 2017).

Several of the technologies available for separation and removal are similar to existing technologies at WWTPs and have been tested in full scale, thus providing valuable operational experience. But implementation would entail additional requirements for maintenance and monitoring. Several technologies are regarded as robust, with stable operation under normal operating conditions (Baresel et al., 2017). Technologies using GAC/BAF are similar to sand filtration systems, which are a common feature of conventional WWTPs and are the easiest to implement from an operational point of view. Installing UF/MBR or ozonation requires taking into account new operational tasks – cleaning the membrane and handling ozone and oxygen.

All the technologies can be used at both small and large WWTPs. However, they depend on a well-functioning main treatment, something which needs to be taken into account for smaller WWTPs that lack conventional treatment. The treatment of nutrients, biological material and suspended solids must be in place prior to the installation of additional treatment for pharmaceutical residues. Treatment with UF/MBR also requires prefiltration through a sieve or similar to protect the membrane.

One aspect to consider when implementing advanced treatment is how the technology handles a dynamic load, with respect to both the removal efficiency and the resource efficiency, which ultimately affects the operating costs of the facility. During ozonation or the addition of powdered activated carbon (PAC) doses, the amount of oxidants/adsorbents as well as contact time or residence time can be controlled based on incoming load, which can vary over the day, the week or the year. When using granular activated carbon (BAF/GAC), the contact time or residence time and choice of materials can affect the removal efficiency.

During operational periods with high hydraulic loads, with the accompanying risk of sludge loss and operational disturbances, it is recommended to by-pass advanced treatment or flow equalisation in order to reduce the risk of such disturbances and ensure resource-efficient treatment (Baresel et al., 2017).

The implementation of advanced treatment in full scale requires further efforts to identify indicators and analytical techniques for measuring the removal efficiency, both during operation and for removal efficiency follow-up.

Table 5. Assessment matrix – technical solutions with regard to facility considerations and operations. Source: Baresel et al. (2017)

	Treatment technology/combination							
	UF	GAC	PAC	BAF	O ₃	PAC-UF	O ₃ -BAF (GAC)	UF-BAF (GAC)
Robust treatment	☺	☺	☺	☺	☺	☺	☺	☺
Tested technologies in full scale	☺	☺	☺	☺	☺	☺ ¹	☺	☺ ¹
Requires little maintenance/monitoring	☺	☺	☺	☺	☺	☺	☺	☺
The solution works without using other technologies	☺	☺ ²	☺ ³	☺ ²	☺ ²	☺	☺ ²	☺
Appropriate facility size	No restriction							
Little space is required ⁵	☺/☺ ⁴	☺	☺/☺ ⁴	☺/☺ ⁴	☺	☺/☺ ⁴	☺	☺/☺ ⁴

☺ = Positive reply; ☹ = Neither positive nor negative; ☹ = Negative reply.

UF = ultrafiltration; GAC = granular activated carbon; PAC = powdered activated carbon; BAF = biologically active filtration; O₃ = ozonation; PAC-UF = the combination of PAC and UF; O₃-BAF(GAC) = the combination of O₃ and BAF with GAC as filter material; UF-BAF(GAC) = the combination of UF and BAF with GAC as filter material.

¹ The combination has not been tested in full scale.

² Extra prefiltration can be beneficial but is not required. However, capacity decreases as particles increase.

³ Impacts sludge management, and an effective separation step is needed.

⁴ Integrated/Separate solution

⁵ Space requirements compared with other technologies/technology combinations in the table. Note that existing infrastructure such as sand filters can be used to install the various technologies.

Table 6 presents a risk assessment with respect to the work environment (Baresel et al., 2017). When handling ozone and dusty materials (PAC), occupational health and safety risks need to be taken into account. Occupational health and safety efforts are needed to reduce risks when handling chemicals for membrane cleaning and liquid oxygen. During ozonation, transformation products are formed that might pose an occupational health risk; this has not yet been studied in detail (Baresel et al., 2017).

Table 6. Assessment matrix – technological solutions with regard to environmental considerations. Source: Baresel et al. (2017).

	Treatment technology/combination							
	UF	GAC	PAC	BAF	O ₃	PAC-UF	O ₃ -BAF (GAC)	UF-BAF (GAC)
Creates a residue with disposal problems	No	No	Yes	No	Yes ¹	Yes	No	No
Risk assessment, occupational health and safety	☹	☹	☹	☹	☹	☹	☹	☹

☹ = No problems, ☹ = Some problems, ☹ = Problems.

UF = ultrafiltration; GAC = granular activated carbon; PAC = powdered activated carbon; BAF = biologically active filtration; O₃ = ozonation; PAC-UF = the combination of PAC and UF; O₃-BAF(GAC) = the combination of O₃ and BAF with GAC as filter material; UF-BAF(GAC) = the combination of UF and BAF with GAC as filter material.

¹ Risk of degradation products with ozonation as sole final treatment

5.4. Overall assessment of environmental considerations

The environmental costs associated with introducing advanced wastewater treatment are primarily related to increased energy consumption and chemical use. To get an idea of which technology has the lowest environmental impact, a systems analysis must be carried out that provides an overall assessment of environmental considerations. This is a complex analysis to perform. For example, the ecotoxic effects on soil and aquatic systems are difficult to quantify (Baresel et al., 2017). A life cycle assessment (LCA) is currently being performed for some of IVL's treatment technologies¹⁹.

ENERGY CONSUMPTION

All the studied treatment technologies and technology combinations will result in an increased use of energy and thus the risk of emissions during energy production. For ozonation and UF technologies, the actual operation of these treatment steps involves an increased energy use. For PAC, GAC, BAF and combinations of these technologies, it is mainly the production and generation of activated carbon that requires additional energy²⁰ (Baresel et al., 2017).

The increased energy consumption for operating the technologies is, as Table 7 shows, the lowest for filter technologies (excl. membrane separation). For other technologies, complementary PAC, GAC or BAF systems are estimated to result in increased energy consumption for large WWTPs (>100,000 PE) of approximately 2-10% (1-6 kWh/(PE, year), for ozonation roughly 20-60% (10-36 kWh/(PE, year) and for UF steps up to 100% (approx. 60 kWh/(PE, year) (Baresel et al., 2017). The estimated additional energy consumption for the operation of a UF step (i.e., 60 kWh) is about as much as it takes to heat up 3,000 homes with direct electric heating for one year (assuming that it requires 20,000 kWh/year)²¹.

Larger facilities are generally more energy efficient than smaller ones²². The additional energy use required by the technologies may change in the future as a result of better implementation and development of the technologies, which in turn can contribute to more efficient processes (Baresel et al., 2017). Alternative energy

¹⁹ In the ongoing SystemLäk project ("Systems for the purification of pharmaceutical residues and other emerging substances"), see Annex 3.

²⁰ Using activated carbon requires resources for manufacturing as well as regeneration in the form of materials (carbon) and energy (gas, steam, electricity) (Baresel et al., 2017).

²¹ $60 \text{ kWh (PE, year)} * 100,000 \text{ PE} = 6 \text{ billion kWh/year} / 20,000 \text{ kWh} = 300 \text{ homes/year} * 10 \text{ facilities} = 3,000 \text{ homes/year}$.

²² Key figures for Swedish WWTPs estimate electrical energy consumption at 50-60 kWh/(PE, year), which means 0.4 kWh/m³ for large facilities (>100,000 PE). For smaller facilities, electricity consumption exceeds 100 kWh/(PE, year), i.e., >0.6 kWh/m³ of treated effluent (Baresel et al., 2017).

sources and more efficient processes can affect potential environmental costs and might look different in the future. The impact of increased energy consumption resulting from advanced treatment on other environmental objectives, mainly on *Reduced Climate Impact and Clean Air*, is therefore difficult to assess at present.

THE USE OF CHEMICALS AND OTHER MATERIALS

Some treatment technologies require chemicals that can cause some environmental impacts during production and use, and thus impact the environmental objective *A Non-Toxic Environment*. Implementing ultrafiltration/MBR requires chemicals for cleaning the membranes, which increases the environmental impact, as well as operational tasks that must be taken into account. Because ozone is a reactive gas, it cannot be compressed and stored in a simple way. This is why it is generated on site, which means that liquid oxygen is handled during ozone generation.

THE FORMATION OF RESIDUES

Table 6 above provides an overall picture of the environmental impact of residues resulting from the introduction of advanced treatment.

The use of powdered activated carbon causes a residue to be formed that needs to be disposed of. This is done either through separately managing the contaminated carbon filter through PAC/sludge management, or having the PAC end up in sewage sludge, which prevents the possibility of using it as fertiliser on farmland.

During ultrafiltration, a concentrate is formed that is returned to the biological treatment where further degradation takes place. When the membrane is cleaned, a retentate is formed that must also be managed by returning it to the biological treatment at the WWTP. In this case, the negative impacts on the environment and occupational health and safety can be minimised (Baresel et al., 2017).

During ozonation, transformation products such as bromate, nitrosamines, formaldehyde and other unknown substances are formed. Some of these are stable and others are biodegradable. They have potential ecotoxicological effects that are difficult to quantify. Post-treatment using biological treatment and/or activated carbon can limit these effects (Baresel et al., 2017).

5.5. Overall assessment when selecting the technology

It is important to select a treatment technology based on the current objectives and local conditions. Examples of factors to consider when selecting the technology and determining an additional treatment step include:

- Existing treatment process at the WWTP. All the technologies depend on a well-functioning main treatment, something which needs to be taken into account for smaller WWTPs that lack complete treatment (Baresel et

al., 2017). The treatment of nutrients, biological material and suspended solids must be in place prior to the installation of additional treatment for pharmaceutical residues. Treatment with ultrafiltration/membrane bioreactor (UF/MBR) also requires prefiltration through a sieve or similar to protect the membrane.

- Existing infrastructure and site-specific conditions. Several technologies can be used either integrated in the main treatment or as additional treatment steps. In addition to the existing treatment process, the existing infrastructure and site-specific conditions such as available space are important considerations. For example, a sand filter can be used for implementing a treatment step with granulated activated carbon (GAC/BAF).
- The incoming load and characterisation of the influent (for example, the percentage of industrial service connections and the amount of extra water, respectively).
- Variations in load and flow over time at the facility, which can result in the need for a dynamic treatment process with greater control. Consider designing the facility so that it can be bypassed during high flows, when the risks of sludge loss and operational downtime are great. Will the treatment of pharmaceuticals be in operation for parts of the year, or in parts of the flow, taking into account load and the sensitivity of the receiving water?
- The implementation of advanced treatment in full scale requires further efforts to identify indicators and analytical techniques for measuring the removal efficiency during operation and for follow-up, as well as for measuring the ecotoxicity of any by-product residues in the effluent.
- Existing sludge use must be taken into account when selecting the technology because some technologies are likely to result in contaminated sludge.
- Economies of scale can be gained when additional treatment is installed, since operational costs (OPEX) and investment costs (CAPEX) are lower for larger WWTPs.
- The goal of the additional treatment step must be taken into account when selecting the technology, as well as the lifetime of the investment. A single treatment technology does not currently provide as complete a treatment as a combination of technologies, but it can be justified depending on site-specific considerations or budget. Technological advances are continuously being made in the field, yet there is a risk that new types of substances will be identified that require separation and removal. This might be one reason to design advanced treatment with the goal of obtaining treatment for a wide spectrum of substances, rather than a few specific substances.

5.6. Conclusions

- Technologies are currently available for the advanced treatment of wastewater to separate and remove pharmaceutical residues. Combinations of different technologies that use various treatment mechanisms – physical processes, oxidative methods, biological methods and adsorption – result in a nearly complete removal of all pharmaceutical substances from the wastewater (Baresel et al., 2017). Ultrafiltration treats only particulate fractions, which means that it does not have a treatment effect on pharmaceutical residues that are soluble in the aqueous phase.
- In contrast to individual technologies, a combination of technologies provides a more comprehensive treatment of more substances, including pharmaceutical residues, microplastics and other hazardous substances. In terms of treatment of other contaminants and microplastics, technology combinations also provide a more comprehensive treatment for more substances than any one technology alone. In addition to the complete removal of microplastics, UF/MBR achieves good removal efficiency for pathogens and bacteria, and thereby also for antibiotics (VRE). Except for nonylphenol, bisphenol A and oestrogen effects (YES), which are more effectively removed via ozonation, adsorptive/biological treatment technologies have a slightly higher removal efficiency for many pollutants (Baresel et al., 2017).
- Several of the technologies available for pharmaceutical separation have similar processes as for existing technologies at WWTPs. For example, technologies using granular activated carbon are similar to the sand filtration systems that are a regular feature of conventional WWTPs and are therefore the easiest to implement from an operational point of view. Most of the advanced treatment technologies presented here have been tested in full scale internationally, providing valuable operational experience. A number of technologies are regarded as robust, with stable operation under normal operating conditions (Baresel et al., 2017). Installing UF/MBR or ozonation requires taking into account new operational tasks – cleaning the membrane and handling ozone and oxygen.
- Advanced treatment results in increased energy consumption, and several of the technologies also involve a greater use of chemicals. This negatively affects other environmental quality objectives. Ozonation leads to the formation of residues with potential ecotoxicological effects that are difficult to quantify. Post-treatment using biological treatment and/or activated carbon can limit these effects.

- It is important to select a treatment technology based on the current objectives and local conditions. Examples of factors to consider when selecting the technology and determining an additional treatment step include: existing treatment process at the WWTP, existing infrastructure and site-specific conditions, characterisation of the influent with regard to composition and hydraulics, current and future sludge use, and objective of the additional treatment step.

6. Socio-economic analysis

This chapter presents drivers and obstacles for introducing advanced treatment at Swedish wastewater treatment plants. In addition, a qualitative discussion of benefits is presented along with information about the costs incurred (treatment costs, environmental costs, etc.) as a result of advanced treatment.

6.1. Drivers for introducing advanced treatment at wastewater treatment plants

Certain drivers may exist that offer positive incentives to introducing advanced treatment at WWTPs in Sweden. Some of these drivers have been identified, but more are possible.

6.1.1. Future regulatory requirements

There are currently no requirements in Sweden on WWTPs to remove pharmaceutical residues. According to current legislation, however, more extensive treatment requirements might be established in an individual environmental assessment defining treatment requirements for Swedish WWTPs that already comply with the EU Urban Waste Water Directive.²³ This is because the directive is a minimum directive. The main policy instruments for Swedish WWTP effluent are the requirements set out in general provisions (including best available technology as stated in Chapter 9, Sections 4-5 of the Environmental Code) and the permitting process in individual cases ('environmentally hazardous activities' under Chapter 9) in which environmental quality standards in accordance with Chapter 5, Sections 2-8 are taken into account. But new or additional requirements for treating environmentally hazardous substances are expected to come into force through legislation or the EU Water Framework Directive²⁴, and these will act as a driver.

THE EU WATER FRAMEWORK DIRECTIVE

According to the EU Water Framework Directive, good ecological and chemical status must be achieved in all water bodies within the EU by 2015 and must not deteriorate unless exemptions have been decided.²⁵ The first priority substance directive²⁶ contained the environmental quality standards for 33 priority substances

²³ Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment.

²⁴ Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy.

²⁵ Guidance from the Agency for Marine and Water Management contains possible exemptions (Chapter 4 Sections 9-10 in the Ordinance on Water Quality Management on exceptions to reaching good status/potential by 2015) (Agency for Marine and Water Management, 2014).

²⁶ Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council.

for which the chemical status in lakes, rivers and coastal waters will be assessed. Since then, 12 new substances have been added.²⁷ A watch list of substances was also created to raise awareness of the presence of these substances and to develop a basis for proposing new priority substances.²⁸ The current list of priority substances does not contain pharmaceutical residues. However, the watch list includes some pharmaceutical substances and hormones: diclofenac (analgesic/anti-inflammatory), ethinyl estradiol, estradiol and estrone (hormones), as well as erythromycin, clarithromycin and azithromycin (antimicrobials), which belong to the class of antibiotics called macrolides.

The EU's list of priority substances and the watch list provide a possible basis for stricter requirements at the EU level for these substances. Individual member states can also choose to impose requirements that are stricter than the EU common provisions (Cimbritz et al., 2016).

Diclofenac, estradiol and ethinyl estradiol are listed as river-basin-specific pollutants under the regulations of the Agency for Marine and Water Management (2013:19) on classification and environmental quality standards with respect to surface waters. Thus, assessment criteria for these three substances are available in Sweden. If these pollutants are discharged in significant amounts²⁹ to a specific water body, the criteria should be used to assess whether the substances are present in concentrations that would jeopardize achieving the environmental quality standard for good ecological status of the water body or would lower the status. The environmental quality standards are applicable to permitting and oversight. The requirements for investigating how operations affect a standard can be far-reaching, for example in the context of permit proceedings. The programmes of measures under the Decree relative to protection of the marine environment (2010:1341) and Ordinance for Water Management (2004:660) can trigger requirements for reassessing the permits.

6.1.2. Other drivers

In addition to regulatory requirements, there are other drivers for introducing advanced treatment at WWTPs. Examples include a desire to be a front-runner, commitment from within the organisation and a cost versus risk analysis for the receiving waters.

The removal of pharmaceutical residues has been ongoing for several years at Astra Zeneca's facility in Södertälje, and the municipal utility company Tekniska

²⁷ Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC in respect of priority substances for water policy.

²⁸ Commission Implementing Decision (EU) 2015/495 of 20 March 2015 establishing a watch list of substances for Union-wide monitoring in the field of water policy in accordance with European Parliament and Council Directive 2008/105/EC (notified under document C(2015) 1756.

²⁹ A significant amount means an amount that poses a risk of adversely affecting the ecological status. If there is a risk that the environmental quality standard is exceeded, this implies a significant amount.

Verken in Linköping is currently introducing a full-scale facility for pharmaceutical removal that will be in operation in 2017. In addition, tests using advanced treatment are underway at several municipal facilities in Sweden including facilities in Kalmar, Stockholm and Uppsala. The following sections describe the drivers behind the decision to apply advanced treatment for Tekniska Verken in Linköping and Kalmar Vatten, based on interviews (see also Annex 6). Finally, the drivers behind the introduction of advanced treatment in Switzerland are also described.

DRIVERS, TEKNISKA VERKEN IN LINKÖPING³⁰

An ongoing installation of an additional ozonation step at the Nykvarnsverket treatment plant in Linköping is the only example available for the implementation of a larger full-scale plant in Sweden.³¹ A risk analysis has been completed showing that the concentrations of several pharmaceutical residues (as measured in the effluent) risk negatively impacting the receiving water body (the Stångån river) (Sehlén et al., 2015).³² The estimated cost – approximately SEK 25 million – has been assessed to be justifiable considering the risk to the environment. Tekniska Verken is not planning to increase the municipal water and sewage fee to cover these costs. However, it has implemented efficiency measures (and will continue to do so) within water and sewage operations to compensate for the increased operating costs of the ozonation step.

According to Tekniska Verken, the main drivers leading to the decision to introduce advanced treatment at Nykvarnsverket were: management's desire to be *a front-runner* and help *benefit business, the environment and society at large*, the *commitment and ability* of employees to do the development work, *access to resources* and the assessment that the *costs were reasonable in relation to the benefits to society* of avoiding environmental risks (i.e., for the receiving waters).

DRIVERS, KALMAR VATTEN³³

Kalmar Vatten plans on building a new WWTP to replace its existing one. In the spring of 2016, the municipal council took a strategic decision and a programme document is now (2017) under development. The schedule for the new WWTP is to start building in 2019 and be fully operational by 2023. Pilot trials were conducted in 2015–2016 with the purpose of using ultrafiltration to remove microplastics. Since then, an additional treatment step using activated carbon was added in order to evaluate the separation and removal of pharmaceutical residues

³⁰ Lövsén (2017). See also Annex 6.

³¹ The treatment plant is dimensioned for 235,000 PE, and is owned and run by Tekniska Verken in Linköping, which has 900 employees of whom roughly 100 are working with water and sewage services.

³² The risk analysis is based on the EC/PNEC factor in the receiving water body (Stångån). EC/PNEC is the ratio between the Environmental Concentration (EC) of the effluent and the Predicted No Effect Concentration (PNEC) (Sehlén et al., 2015).

³³ Ullman and Zhao (2017). See also Annex 6.

and other organic pollutants.³⁴ The strategic decision includes an investment in a UF facility, but a decision on the introduction of pharmaceutical treatment has not yet been taken (April 2017). A multi-criteria analysis was performed in 2012 as a basis for designing the new WWTP. The analysis took into account discharges to receiving waters and spread of infection.³⁵ A relatively large study that specifically focused on future treatment requirements was also conducted, and is continuously updated as global developments are monitored (Urban Water, 2012).

According to Kalmar Vatten, the main drivers behind development efforts to introduce advanced treatment in the new WWTP were: management's desire *to be a front-runner*, the *commitment and ability* of employees to carry out development work, a *political interest* in the environmental risks, and the *expectation of future legislation* on the treatment of pharmaceutical residues. The *precautionary principle* has also been a key driver (based on risks such as the spread of antibiotic-resistant bacteria). However, the cost-benefit justification for introducing advanced treatment considering the properties of the receiving waters was not considered strong enough.

DRIVERS, SWITZERLAND

Switzerland was the first country to push for legislation involving large-scale, comprehensive WWTP development. Its legislation came into force in January 2016. However, it has taken some time for this legislation to be applied, and several extensive investigations have taken place. It has taken roughly 10 years to move from problem description to legislation. The upgrades are scheduled for completion in 2040 (that is, over a 25-year period). The drivers that led to the full-scale introduction of advanced treatment for micropollutants were, initially, the results from several studies that detected *effects on the aquatic environment* from endocrine disruptors. In addition to the environmental impacts, the studies also found a *contamination risk for drinking water*. Surveys also revealed that *public opinion was favourable* and that there was a *willingness to pay for actions* (see 6.3.4). Generally speaking, Switzerland has sensitive receiving waters because most of the waters are used to supply drinking water. Several countries downstream are also impacted by changes in the aquatic environment in Switzerland. It has been assessed that advanced treatment can bring about significant improvements in water quality, and that cost-effective technologies are available (Cimbritz et al., 2016).

³⁴ This pilot project will last for one year and will end in February 2018.

³⁵ The multi-criteria analysis is based on the following criteria, ranked in order of precedence: 1: Discharge to water and contamination. 2: Reliable and robust WWTP (relatively small staff and no expansion capacity at the WWTP). 3: Flexibility for future expansion. 5: Future flexibility with respect to tougher regulatory requirements (on nitrogen, phosphorus, pharmaceuticals) (Urban Water, 2012).

In total, approximately 100 of 750 facilities will be upgraded. Some minor facilities will be closed and transferred to larger facilities where the treatment is considered to be more cost effective. WWTPs of different sizes must, according to the new legislation, be upgraded for various reasons. Facilities with a load of at least 80,000 PE are upgraded to reduce the overall load of micropollutants. These upgrades are expected to cover more than half of the population. Facilities designed for a minimum of 24,000 PE with discharges to lakes are being expanded to protect certain drinking water supplies. WWTPs with loads greater than 8,000 PE with discharges to receiving waters with insufficient dilution are being expanded to protect particularly sensitive receiving waters (Cimbritz et al., 2016).

6.2. Obstacles for introducing advanced treatment at wastewater treatment plants

Some obstacles for introducing advanced treatment at WWTPs in Sweden involve negative incentives primarily due to costs related to upgrades. Some of these obstacles have been identified, but more are possible.

6.2.1. Investment needs

The main challenges faced by the water and wastewater industry involve strategic actions and increased investment needs to secure long-term future sustainability. This is true for the entire field of water and sewage, which must try to tackle issues like ensuring a secure water supply, adapting to climate change and renewing sewage collection systems while meeting tougher new treatment requirements. Water and sanitation services are in good standing today, but more strategic actions and investments are needed to ensure long-term sustainability. Expertise and staffing are relatively good when it comes to operational aspects, but resources are lacking for long-term strategic efforts (Swedish Water and Wastewater Association, 2016). Many facilities have been operating since the 1960's and 1970's, and are currently undergoing renovation and refurbishment. The need to boost future investment in many WWTPs can represent an obstacle, with the potential for burdensome costs for the facilities and possibly the municipalities. Figure 4 shows the development of wastewater treatment technology between 1940 and 2014 in Swedish WWTPs. The biggest development took place during the 1970's, when heavy investments were made in biological-chemical treatment (Swedish EPA, 2014).

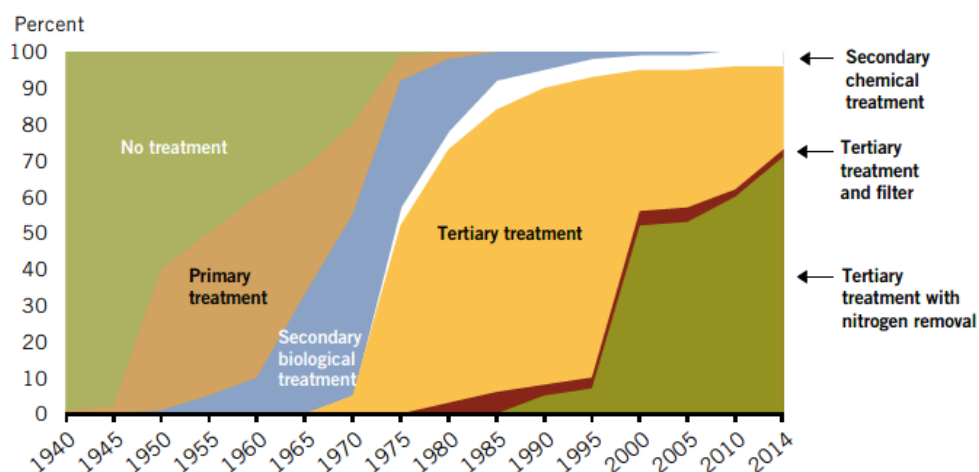


Figure 4: Development of wastewater treatment technology in Sweden, 1940–2014.
Source: Swedish Environmental Protection Agency, 2014.

There can also be technical barriers associated with the costs of upgrading an existing WWTP with advanced treatment technology. All the technologies studied in this commission, for example, assume a well-functioning main treatment. Existing infrastructure and other site-specific conditions (for example, whether sufficient physical space is available) can also constitute a major obstacle to installing advanced treatment technology. (The technological prerequisites are described in more detail in Chapter 5.)

Small water and sewage organisations with fewer than 20,000 people are facing greater challenges than others, primarily in terms of securing long-term viability. Future investment needs might be more difficult to manage in municipalities with smaller organisations. Longer distances, where even fewer people pay for water and sewage services in relation to the necessary infrastructure, also affect the investment outlook. Cooperation between municipalities improves the viability of the operations, and municipalities that participate in different types of collaborative solutions are expected to be able to meet future challenges (Swedish Water & Wastewater Association, 2016).

The costs of water and sewage services in Sweden today are 99% financed by the sewage fees charged to connected households and industries. The remaining one percent is financed through municipal taxes. Larger municipalities generally have full cost recovery for the water and sewage costs (Swedish EPA, 2012). However, small municipalities with a small revenue base for water and sewage services generally find it more difficult to finance advanced upgrades of their WWTPs since their ‘basic requirements’ (e.g., sewerage collection systems) often take priority. Today, there is a shortage of qualified staff, particularly in smaller water and sewage organisations that must often rely on consultants for preparation, planning, design and implementation (Swedish EPA, 2012). For smaller organisations, costs and the ability to find workers with the right skill sets for process and operational staff are considered major obstacles to introducing additional treatment

technologies (Baresel et al., 2017). Most municipalities with fewer than 2,000–50,000 PE currently lack the expertise needed to be able to order and invest in advanced wastewater treatment (Finnson, 2017b).

Sections 28 and 30 of the Public Water Services Act regulate what the water and sewage fee include. Section 28 stipulates that, in addition to the disposal of the water, the fee should also cover the costs of treating the water when necessary for the protection of human health and the environment (here, the need for advanced treatment technology could be included). Section 30 regulates the so-called full cost principle: the fee must not exceed the costs necessary to organise and operate public water and sewage facilities. Development costs, such as the costs of technology development, are possible examples of such necessary costs.³⁶ However, the water and sewage fee must be fair and equitable in accordance with Section 31.

6.2.2. Administrative costs

The administrative costs resulting from policy instruments can be a burden on individual actors and represent a potential obstacle for the WWTP to introduce a more advanced treatment technology. Introducing advanced treatment at a WWTP normally requires a permit or notification obligation, which is associated with certain costs for the facility. Under Chapter 16, Section 2 of the Environmental Code, a permit may be limited to cover changes only (an amendment permit). This means that the permit for the entire operation does not necessarily need to be reviewed. A permit review can otherwise be resource- and time-consuming for many parties³⁷. If the operation does not require a permit in accordance with Chapter 1, Section 4 of the Environmental Permitting Regulations (2013:251), the notification obligation in accordance with Chapter 1, Section 11 applies. This means that a notification can suffice if there is a minor change. A permit review is required if the change itself is subject to permitting, or if the change poses a risk of detriment to human health or the environment. This means that a notification can suffice if there is a minor change that is not considered detrimental.

6.3. Benefits of advanced treatment

The analysis in Chapter 4 indicates that there is a need for advanced treatment, at least at some Swedish WWTPs. The environmental impacts, however, have been difficult to estimate because they vary throughout the country. It is evident, though, that negative environmental impacts could be avoided by introducing advanced treatment at WWTPs that would contribute to increased environmental benefits. In this commission, it has not been possible to quantify these benefits at Swedish WWTPs because of the uncertainties surrounding the effects and not knowing what the reduction target is. One thing is clear, however: society stands to gain

³⁶ Govt Bill 2005/06:78. Public Water Services (Bill 2005/06:78), page 87.

³⁷ On average, 1-2 years per operation (Swedish EPA, 2012).

environmental benefits. The following sections describe arguments for societal benefits of introducing advanced treatment.

6.3.1. Environmental impacts

Several studies have shown that pharmaceuticals can have adverse effects in the aquatic environment, including endocrine-disrupting effects and the risk of the spread of antibiotic resistance. For one, the MistraPharma³⁸ research programme demonstrated in laboratory experiments the effects of various types of pharmaceuticals at levels measured in the environment. There are also many scientific articles that have shown the adverse effects on ecosystems and species (see also Chapter 4). Additional negative changes in ecosystems could be reduced, or possibly avoided, by reducing the concentrations of pharmaceuticals and other hazardous substances using advanced treatment technology. Thus, the costs associated with such negative environmental impacts could be better avoided (i.e., provide increased environmental benefit).

6.3.2. Health effects

There is currently a lack of knowledge about the potential health effects on humans resulting from the discharge of pharmaceutical residues into the aquatic environment. But the release of antibiotics into the environment, for instance, poses a risk of the spread of antibiotic resistance (see Chapter 4). It is also clear that combination effects must be more rigorously considered when assessing health and environmental risks, as we know little about the future impact on our health resulting from the interaction of different substances (see, for example, Swedish Medical Products Agency 2014 and references). Cimbritz et al. (2016) argue that the potential health effects associated with protecting drinking water can act as more of a major driver for taking concrete action than the various ecotoxicological effects. The authors note that pharmaceutical residues in the water bodies do not pose a direct threat to human health, although their presence provides justification from a consumer confidence perspective (Cimbritz et al., 2016). Today, there are considerable safety margins for individual substances. This indicates that significant adverse effects on human health are not particularly likely at current exposure levels in drinking water. However, there are gaps in the assessment of the risks associated with long-term exposure for individual drugs, mixtures and in combination with other chemical substances (Wallberg et al., 2016).

6.3.3. The precautionary perspective

Many pharmaceutical compounds are persistent and, despite low concentrations, adversely affect aquatic organisms (see Chapter 4). In certain combinations, different substances can also produce effects that are today difficult to predict. To avoid unnecessary risks to the environment, introducing advanced treatment can be justified precisely because of the uncertainty surrounding future effects. Although we currently know very little about future large-scale implications for society, it is

³⁸ MistraPharma Research Programme 2008–2015. Final report (www.mistrapharma.se).

possible that the costs associated with these implications might be lower if we take action now instead of waiting.³⁹ Restoring damaged ecosystems afterwards can be extremely expensive – or even impossible – if irreversible effects on ecosystems have occurred. The overall effect on the economy can be difficult to assess, but modelling of ecosystem changes often indicate changes at the societal level. The Baltic Sea is a clear example showing that damage to the marine ecosystem cannot be restored afterwards. An elimination of top-tier predators has led to trophic cascade effects⁴⁰ in the Baltic Sea's marine ecosystems. Cod (*Gadus morhua*), a top-tier predator in the Baltic Sea food chain, has been fished out, which is probably the main reason for the persistent algal blooms in the Baltic Sea (Österblom et al., 2007). The benefit of reducing algal blooms in the Baltic Sea has been estimated to exceed the cost to society (see Swedish Agency for Marine and Water Management, 2013).

6.3.4. Example quantification of benefits nationally (and costs)

As mentioned in section 6.1.2, Switzerland is one of the first countries that started to introduce large-scale advanced treatment in municipal WWTPs. It is also the only example of benefits quantification on a larger scale. Logar et al. (2014) estimated the benefit of upgrading the WWTP in Switzerland by estimating people's willingness to pay in order to reduce the potential environmental and health risks.⁴¹ The study estimates the average willingness to pay at CHF 100 (about SEK 900) per household annually in order to reduce the potential risk to the environment and public health. Aggregated to an upgrade of WWTPs to a river basin level, this means that the benefit is estimated at an annual value of CHF 155 million (about SEK 1.4 billion). The cost of upgrading 123 WWTPs was estimated at CHF 133 million annually (about SEK 1.1 billion), or CHF 86 (about SEK 760) per household connected to these WWTPs. In other words, the benefit exceeds the costs in this study (Logar et al., 2014).

The assessment, in this case, shows justification for the cost based on society's preferences.⁴² Switzerland, however, is a special example because many of the receiving waters are drinking water sources. And discharges there also affect the

³⁹ Compare climate action where Stern, N. (2006) has demonstrated this.

⁴⁰ In trophic cascades, the biomass of a trophic level (level in the food pyramid) is governed by the one above it. Predators thus regulate their prey populations rather than the biomass of the prey being limited by its food. For example, if trophic cascades regulate the composition of plankton, the fish will be able to influence the biomass of phytoplankton (Marine Environmental Research Institute, 2012).

⁴¹ In a so-called public stated preference study, people are asked about their willingness to pay in a hypothetical scenario.

⁴² A fund was set up for financing. During the introduction period, various stakeholders were informed through different types of consultations. At the same time that the legislation came into force, the water and sewage fee was raised an average of CHF 9 per person per year (about SEK 80). When the expansion of the facility is completed and it is put into operation, 75% of the investment costs from the fund will be recovered. When the facility has been upgraded, the recovery order for the fund will cease, and instead OPEX and CAPEX for the upgraded facility will be paid off. For large facilities, this is usually less than CHF 9 (Cimbritz et al., 2016).

waters of several other countries. It is therefore not possible to directly compare the benefit estimate with Swedish conditions.

6.4. Costs of advanced treatment

The costs associated with different measures are listed below, i.e., the investment and operational costs of the technologies studied. Costs associated with policy instruments (such as taxes, subsidies, fees, discharge allowances, permits and regulations) are not included. Such expenses, however, will arise when implementing any of these instruments for treatment measures.

6.4.1. Treatment costs

The estimated treatment costs for the studied treatment technologies are indicated in Table 7. These costs include total investment costs, operational costs and costs per cubic metre of treated wastewater.⁴³ Estimated electricity consumption for operating the different technologies is also indicated. The cost estimates are based on different data, but mainly on comparable cost calculations and quotations from several Swedish and international technology suppliers and contractors (Baresel et al., 2017). For the assumptions underlying the cost estimates, such as the dimensioning flow, the purchase price for electricity and activated carbon, personnel costs, interest rates and economic lifespan, see Baresel et al. (2017).

Estimates are indicated for five different sizes of facilities. The costs vary widely, both between different technologies and different WWTP sizes. With the assumptions made, effective treatment for the studied substances for facilities larger than 100,000 PE is expected to be achieved for less than SEK 1/m³ of treated effluent water. For smaller facilities (2,000–20,000 PE), the costs of some of the treatment technologies can reach slightly more than 5 SEK/m³. Uncertainty, however, is greater for smaller WWTPs and, in particular, for the smallest facility size (2,000 PE). The uncertainty for smaller facilities is mainly because they were not the focus of the SystemLäk project and are not a preferred size for technology providers. These are indicated in italics in Table 7. The stated costs are influenced by several different parameters and are based on many assumptions, so they should be considered with caution. Furthermore, the stated costs can only be verified when several full-scale facilities have been installed.⁴⁴

It can be discerned from Table 7 that the annual capital expenditures decrease compared with the operating costs based on the facility's size. This decrease is most obvious for technologies that use ultrafiltration (UF) and combinations in which UF is used as a treatment step. For technology combinations, the investment

⁴³ Treatment costs per cubic metre of treated effluent (SEK/m³) are calculated by dividing the total annual investment costs and operation costs by the total annual effluent treated by the WWTP. The dimensioning flow used for all facilities is 150 m³/(PE, year) (see assumptions in Baresel et al., 2017).

⁴⁴ For detailed information about the cost estimates for individual technologies, see Baresel et al. (2017).

costs generally consist of the sum of the different technologies included in the combination (Baresel et al., 2017).

The extra electricity consumption for operating the technologies is estimated to be between 0.01 and 0.55 kWh/m³ depending on the technology. Electricity consumption for operation is the lowest for GAC, BAF and PAC and peaks when UF is included either as a single technology or a technology combination (see also section 6.4.3). For technologies where energy consumption is a major part of the operating cost, bigger facilities mean better energy efficiency; as a result, costs decrease with increasing facility size (Baresel et al., 2017).

The estimated costs are lower than previous estimates made.⁴⁵ Technology combinations bring higher installation and operational costs compared with the implementation of individual technologies. From a purely financial point of view, ozonation is the most inexpensive additional treatment step. This is due to the lower operating costs compared with technologies like granulated activated carbon (GAC), powdered activated carbon (PAC) and biologically active filtration (BAF). The removal efficiency, however, is slightly better for the latter technologies (Baresel et al., 2017).

⁴⁵ For example, estimates made by Wahlberg et al. (2010).

Table 7. Cost estimates for technologies and technology combinations. Source: Baresel et al. (2017).

Treatment technology/combination								
	UF ¹	GAC	PAC ²	BAF ³	O ₃	PAC-UF ⁴	O ₃ -BAF (GAC) ⁵	UF-BAF (GAC) ⁴
Installation CAPEX (MSEK)								
2,000 PE	11-14	(4)	0.15	(4)	1.4-5	14	(5-9)	15-18
10,000 PE	13-19	6.5	0.2	6.5	2-7.5	19	8.5-14.5	19-25
20,000 PE	17-25	7.5	0.25	7.5	3.4-9	25	11-16.5	22-32
100,000 PE	50-75	17.5	0.8	17.5	10.5-20	75	18-37	67-93
500,000 PE	210-320	50	3.5	50	28-60	320	58-110	260-370
Annual capital expenditure CAPEX (MSEK/year)								
2,000 PE	0.8-1	(0.3)	0.01	(0.3)	0.1-0.4	1	0.4-0.7	1.1-1.4
10,000 PE	1-1.5	0.4	0.015	0.6	0.15-0.55	1.4	0.6-1	1.4-1.9
20,000 PE	1.3-1.9	0.5	0.02	0.7	0.3-0.7	1.8	0.8-1.2	1.6-2.4
100,000 PE	3.6-5.5	1.2	0.06	1.6	0.8-1.5	5.4	1.3-2.5	5-7
500,000 PE	16-25	3.4	0.25	4.6	2-4.5	23	4.3-7.5	19-27
Operating expenditure OPEX (MSEK/year)								
2,000 PE	0.4-0.5	(0.7)	0.35	(0.7)	(0.2)	0.6	(0.8)	1.1-1.2
10,000 PE	0.6-1	0.9	1	0.5	0.3	1.8	0.7	1.1-1.5
20,000 PE	0.8-1.6	1.6	2	0.9	0.4	3.1	1.2	1.7-2.5
100,000 PE	3.5-6	7.8	8.5	4	1.5	14	4.9	7.5-10
500,000 PE	14-25	38	43	19	6.5	65	22.5	33-44
Total cost (SEK/m ³)								
2,000 PE	3.5-4.5	1-1.2	1.1	1-1.2	0.55-0.9	5.3	1.5	4.5-5.7
10,000 PE	1-1.5	0.8-1	0.7	0.7-1	0.25-0.55	2.1	1.1	1.7-2.5
20,000 PE	0.7-1.1	0.7-1	0.6	0.5-0.8	0.23-0.35	1.6	0.75	1.2-1.9
100,000 PE	0.5-0.75	0.5-0.7	0.57	0.35-0.6	0.19-0.20	1.3	0.50	0.8-1.4
500,000 PE	0.4-0.65	0.3-0.6	0.55	0.2-0.5	0.14-0.15	1.2	0.40	0.6-1.2
Operational electricity consumption (kWh/m ³)	0.1-0.5	<0.01	0.01-0.05	<0.01	0.1-0.3	0.1-0.55	0.1-0.3	0.1-0.5

UF = ultrafiltration; GAC = granular activated carbon; PAC = powdered activated carbon; BAF = biologically active filtration

O₃ = ozonation; PAC-UF = the combination of PAC and UF; O₃-BAF(GAC) = the combination of O₃ and BAF with GAC as filter material; UF-BAF(GAC) = the combination of UF and BAF with GAC as filter material

¹ Based on different types of UF

² Based on different types of UF

³ Using the same technology as GAC filters but with higher capacity and thereby less GAC exchanges through biological activity

⁴ Based on cost estimates for the sum of individual technologies

⁵ Based on cost estimates for both this specific technology combination and the sum of individual technologies

An attempt to extrapolate costs to all WWTPs in Sweden (greater than 2,000 PE) means an estimated total cost of between approximately 241 million and 2.1 billion Swedish kronor per year. This corresponds to approximately 55-480 kronor per household per year⁴⁶ (see calculations in Table 8).

The scaling-up costs for all WWTPs in Sweden is lower than previous estimates made, for example, in Wahlberg et al. (2010)⁴⁷. The estimated total cost is comparable with the operational cost of Sweden's water and sewage operations, which totalled 17 billion kronor in 2012 (Finnson, 2017a). The costs can also be put in perspective considering that between 1971 and 1979 the Swedish state invested close to 1.5 billion kronor (equivalent to about 5.5 billion at 2016 prices) for the upgrade of municipal WWTPs in Sweden (Swedish EPA, 2014).

Table 8. Extrapolation of treatment costs

Extrapolation to 431 WWTPs (a total of 8,049,753 connected persons (PE))
WWTPs for 2,000–10,000 PE, (246 facilities)
150 m ³ /(PE, year) * 678,682 PE = 101.8 million m ³ /year * 0.55–5.7 SEK/m ³ Total = 56–580 million SEK/year
WWTPs for 10,000–20,000 PE (71 facilities)
150 m ³ /(PE, year) * 602,021 PE = 90.3 million m ³ /year * 0.25–2.5 SEK/m ³ Total = 23–226 million SEK/year
WWTPs for 20,000–100,000 PE (95 facilities)
150 m ³ /(PE, year) * 2,542,267 PE = 381 million m ³ /year * 0.19–1.4 SEK/m ³ Total: 73–534 million SEK/year
WWTPs for 100,000–500,000 PE (19 facilities)
150 m ³ /(PE, year) * 4,226,783 PE = 634 million m ³ /year * 0.14–1.2 SEK/m ³ Total: 89–761 million SEK/year
Total: 241 million – 2.1 billion SEK/year

WHAT AFFECTS COSTS THE MOST?

Site-specific conditions affect treatment costs to the greatest extent. For example, unused infrastructure in some WWTPs (such as old sand filters) plays a large part in the choice of additional technologies when using these can lead to significantly lower investment costs.

The treatment flow (dimensioning flow) can also vary widely from plant to plant. The flow of water requiring treatment thus becomes an important parameter that can have a major impact on treatment costs per cubic metre of treated effluent. Here, costs are based on an average load of 150 m³/(PE and years).

⁴⁶ Under the assumption that there are 431 WWTPs greater than 2,000 PE in Sweden (Swedish EPA and Statistics Sweden, 2016). The dimensioning flow is also assumed to be 150 m³/(PE, year).

⁴⁷ Where the total cost is estimated to be between 1.2 and 5.7 billion per year (Wahlberg et al., 2010).

This is an average size for large Swedish WWTPs and has been used for all the facilities in the calculations. If the facilities need to be dimensioned for much higher flows (e.g., for snowmelt or heavy rains), the investment costs will increase (Baresel et al., 2017).

A possible greater market demand for the technology, as well as more lessons learned from actual installations, will likely affect costs going forward. The consumption of activated carbon dominates operating costs for both PAC and GAC, which means that the price development of carbon affects the costs. Even future developments, for example using biochar, can impact costs. The costs of the membrane and its electricity requirements mainly affect the costs of technologies that include UF. The specified costs for UF can thereby be reduced if the demand for electricity is reduced (unless there is a spike in electricity prices). Even for ozonation, the consumption of electricity and/or liquid oxygen (LOX) greatly affects the cost per cubic metre of treated effluent. The price development of LOX is therefore relevant. For BAC, filter replacements constitute the dominant cost over time, so the costs of the filter material thus have an impact. For technology combinations, the different factors from the individual technologies affect the costs (Baresel et al., 2017).

Indirect costs that may arise when introducing the studied technologies are not included in the estimates but might affect the costs. For example, extended or separate sludge management is not included in the calculations but above all need to be considered when using PAC and additional UF.

6.4.2. Effect/benefit of specific technologies

None of the treatment technologies studied can alone achieve a complete removal (meaning greater than 90%) of pharmaceutical residues and other studied contaminants. A broad treatment of micropollutants is obtained only when different treatment mechanisms are combined. In other words, the combinations of different technologies that use various treatment mechanisms – physical processes, oxidative methods, biological methods and adsorption – result in a nearly complete removal of all pharmaceutical substances.

6.4.3. Environmental costs

The environmental costs associated with the technologies studied are primarily related to increased energy consumption and chemical use (see also section 5.4).

All the studied treatment technologies and technology combinations will result in an *increased use of energy* and thus the risk of emissions during energy production. For ozonation and UF technologies, the actual operation of these treatment steps involves an increased energy use. For PAC, GAC, BAF and combinations of these technologies, it is mainly the production and generation of activated carbon that

requires additional energy.⁴⁸ The increased energy consumption for operating the technologies is, as Table 7 shows, the lowest for PAC, GAC and BAF. For other technologies, complementary PAC, GAC or BAF systems are estimated to result in increased energy consumption for large WWTPs (>100,000 PE) of approximately 2-10% (1-6 kWh/(PE, year), for ozonation roughly 20-60% (10-36 kWh/(PE, year) and for UF steps up to 100% (approx. 60 kWh/(PE, year) (Baresel et al., 2017). The estimated additional energy consumption for the operation of a UF step (60 kWh) is about as much as it takes to heat up 3,000 homes with direct district heating for one year (assuming that it needed 20,000 kWh/year).⁴⁹

Larger facilities are generally more energy efficient than smaller ones⁵⁰. The additional energy use required by the technologies may change in the future as a result of better implementation and development of the technologies, which in turn can contribute to more efficient processes (Baresel et al., 2017). Alternative energy sources and more efficient processes can affect potential environmental costs and might look different in the future. The impact of increased energy consumption resulting from advanced treatment on other national environmental objectives, mainly on *Reduced Climate Impact* and *Clean Air*, is therefore difficult to assess.

In Switzerland, the electricity consumption is estimated to increase by 5-30%, which corresponds to an increase in the country's total energy consumption of 0.1%. It is expected that more energy-efficient WWTPs and renewable energy production will compensate for this. However, since the conversion takes place over a 25-year period it is expected that room will be created for choosing new, resource-efficient technologies (Cimbritz et al., 2016).

Some treatment technologies require chemicals that can cause some environmental impact during production and use, and thus affect the national environmental objective *A Non-Toxic Environment*. There is also some risk that new potentially toxic contaminants will form as a result of certain technologies that use oxidative treatments (see also section 5.4).

6.4.4. Other costs

Other costs that might arise include labour costs and costs related to monitoring, skills development, and on-site health and safety. For some of the described treatment technologies, the knowledge and experience of the WWTP staff must be built up. But through knowledge transfer and experience transfer from installations

⁴⁸ Using activated carbon requires resources for production and regeneration in the form of materials (carbon) and energy (gas, steam, electricity) (Baresel et al., 2017).

⁴⁹ 60 kWh (PE, year) * 100,000 PE = 6 billion kWh/year / 20,000 kWh = 300 homes/year * 10 facilities = 3,000 homes/year.

⁵⁰ Key figures for Swedish WWTPs estimate electrical energy consumption at 50-60 kWh/(PE, year), which means 0.4 kWh/m³ for large facilities (>100,000 PE). For smaller facilities, electricity consumption exceeds 100 kWh/(PE, year), i.e., >0.6 kWh/m³ of treated effluent (Baresel et al., 2017).

that already use additional treatment technologies, the costs should be able to be reduced.

None of the described technologies and combinations involve any special operational considerations for normal operation since several of the technologies are similar to existing technologies at the facilities⁵¹ (see also section 5.3). For all treatment technologies, operation at high loads requires additional monitoring and control to avoid downtime. Some technologies require more maintenance and monitoring than others. For example, extra work is needed continuously (during carbon dosing) or periodically (when replacing filter materials). Supplementing existing treatment with other treatment technologies can sometimes affect other process-related areas of the WWTP (e.g., sludge management), which may give rise to costs in each specific case (Baresel et al., 2017).

Most of the studied technologies and combinations do not pose any major occupational health or safety problems (as indicated above). But certain aspects of the work environment do need to be taken into account. For example, handling ozone or dusty material (PAC) might involve occupational health and safety risks. Handling chemicals when using UF technologies or liquid oxygen can also pose some of these risks (Baresel et al., 2017).

6.5. Conclusions

This chapter has highlighted several considerations that should be taken into account when implementing advanced treatment at WWTPs in Sweden. The following sections provide an overall assessment of these considerations.

6.5.1. Costs versus benefits

From a socio-economic perspective, advanced treatment is ideally introduced at WWTPs where the need is greatest based on the characteristics of the receiving waters. If benefits exceed costs based on the environmental and health objectives for a specific recipient, then it is socio-economically efficient. This does not necessarily mean that it is reasonable from a distributional perspective. That is, even if it is profitable for all of society to introduce advanced treatment at a WWTP based on the characteristics of the receiving waters, it can be costly for some individual actors or for a particular geographic region. A quantification of the benefits has not been possible because of the difficulty of estimating the environmental impact, and because no reduction target is available. It is clear, however, that the introduction of advanced treatment at Swedish WWTPs will bring increased environmental benefits to society (because costs of damage can be avoided), and it is justified under a precautionary approach. Repairing damages afterwards can have major socio-economic consequences.

⁵¹ For example, GAC/BAF technologies are similar to the sand filtration systems that are common in conventional WWTPs in Sweden (Baresel et al., 2016).

WHAT IS REASONABLE?

If benefits exceed costs in a specific catchment area or for a specific receiving water body (see the description of the sensitivity of different receiving waters in 4.3), installing advanced treatment technology appears justified. During implementation, it could perhaps be more efficient in some cases to connect smaller WWTPs to larger facilities than to install advanced treatment technology in the smaller WWTP. In other cases, introducing advanced treatment is justified even in small WWTPs from a cost-benefit perspective. However, in some cases upstream work might be more inexpensive for smaller facilities than introducing advanced treatment technologies.⁵²

6.5.2. Costs

Effective treatment for the studied substances for facilities greater than 100,000 PE can be achieved using several of the treatment technologies for less than 1 SEK/m³, based on the assumptions made. For smaller facilities (2,000-20,000 PE), the costs of some of the treatment technologies can total about 5 SEK/m³. Because the stated costs are influenced by several different parameters and are based on many assumptions, they should be considered with caution. The costs can also change with time as more knowledge becomes available.

Today, we do not know which WWTPs or how many of them could potentially be relevant to upgrade with advanced treatment technology. An attempt to extrapolate costs to all WWTPs in Sweden greater than 2,000 PE (431 facilities) means an estimated total cost of between approximately 241 million and 2.1 billion kronor per year, which corresponds to approximately 55–480 kronor per household per year. For purposes of comparison, the operational cost of Sweden's water and sewage operations totalled 17 billion kronor in 2012. The estimated costs are lower than earlier estimates by Wahlberg et. al (2010), for example.

ECONOMIES OF SCALE

Generally, completed estimates show that economies of scale in the form of cost savings can be achieved for major WWTPs for many of the studied treatment technologies. For technologies where energy consumption makes up a major part of the operating cost, larger facilities provide better energy efficiency and reduce costs as facility size increases.

The costs for small facilities (2,000 to 10,000 PE) differ more than between large facilities, partly because of uncertainties in the estimates. It is clear, however, that investment costs play a dominant role for smaller facilities. The studied technologies further assume that the WWTP already has a well-functioning main treatment. Also, smaller WWTPs might lack an efficient system for the effective treatment of nutrients, organic substances and particles. If so, the investment costs

⁵² Some inputs, however, cannot be remedied at the source (e.g., medication for consumption or the introduction of microplastics from traffic) (Swedish Medical Products Agency, 2014).

will be higher. For example, advanced nitrogen removal is not part of the treatment process in many WWTPs.⁵³

ENVIRONMENTAL COSTS

The technologies studied result in increased energy use that brings with it the risk of emissions and thus environmental costs. The extra electricity consumption for operating the technologies is estimated to be between 0.01 and 0.55 kWh/m³ depending on the choice of technology. Electricity consumption for operating the technology is highest when ultrafiltration is included. At large facilities (100,000 PE), the increased energy use would represent an increase of approximately 2-10% when implementing a PAC, GAC or BAF system, approximately 20-60% for ozonation, and up to 100% for a UF step (about 60 kWh/(PE, year)).

The additional energy use might change in the future as a result of more energy-efficient processes. Therefore, it is not possible to assess the extent of the impact on other environmental objectives.

6.5.3. Incentive structure for wastewater treatment plants

The incentive structure for introducing advanced treatment technology at WWTPs is crucial at the implementation state. Some drivers and obstacles facing national WWTPs have been identified, and there are certainly more that are not identified here.

DRIVERS

Expected new or additional legislation is a strong driver for WWTPs to introduce additional treatment steps. Several WWTPs have already begun preparing for the introduction of future requirements on the treatment of pharmaceutical residues. Another driver is that the costs are considered reasonable compared with the benefits and/or risk to the receiving waters. The precautionary principle is a key driver due to factors such as the risk of antimicrobial resistance. Success factors that will enable a WWTP to develop advanced treatment include organisational commitment, resource capabilities and expertise. Policy decisions, political interest and positive public opinion can also be important drivers.

OBSTACLES

The primary obstacles identified for the WWTPs are the challenges currently faced by Swedish water and sewage facilities, with their great investment needs including financing that can ensure long-term sustainability (e.g., climate adaptation and renovation of sewerage collection systems). This means that there are financial barriers especially for smaller municipalities that find it more difficult to achieve

⁵³ WWTPs greater than 10,000 PE are covered by the waste directive (1991/271/EC) and thus have more stringent requirements in certain areas, such as nitrogen removal (Swedish EPA, 2012). For nitrogen removal, a geographical limit also exists (Swedish EPA, 2014).

full cost recovery. The distributional effects thus become an important aspect to consider when designing policy instruments. The interests of society at large might also conflict with local priorities, which may need to be taken into account. Technology barriers can also be present due to site-specific conditions. Finally, legal issues could pose obstacles for the WWTPs in the form of burdensome administrative costs.

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Annex 1 The Commission

Government Decision 1:51

The Swedish
Government

2015-12-17 M2015/04328/Ke

The Ministry of the Environment and
Energy

Naturvårdsverket
106 48 Stockholm

Commission to investigate the prerequisites for use of advanced treatment for the removal of pharmaceutical residues from wastewater

The Government's decision

The Government hereby instructs the Swedish Environmental Protection Agency (EPA) to investigate the prerequisites for use of advanced treatment for the removal of pharmaceutical residues from wastewater in order to protect the aquatic environment. The EPA shall analyse the need for advanced treatment, the technological solutions available including their advantages and disadvantages, and other consequences of the use of advanced treatment. The commission shall focus on wastewater treatment plants serving a population of more than 20,000 people or that receive wastewater with a pollutant load corresponding to more than 20,000 population equivalents (PE).

The EPA shall report its findings to the Government Offices (Ministry of the Environment and Energy) by 1 May 2017.

Background

One of the responsibilities of the municipalities is to provide water services. In accordance with section 6 of the Public Water Services Act (2006:412), the municipalities are obliged to provide water supply and sewerage services in a wider context if necessary for the protection of human health or the environment. The environmental consideration was added in 2007. Water services are financed by fees from the water and sewage collective in accordance with the full cost principle under the Municipality Act, regardless of whether the principal is a municipal board, a private company or an association of local authorities.

In accordance with Chapter 28, Section 1 of the Environmental Permitting Regulations (2013:251), anyone wishing to operate a wastewater treatment plant with a service connection of more than 2,000 persons or that receives wastewater with a pollutant load corresponding to more than 2,000 PE must apply for a permit with the Environmental Appeal Delegation. The County Administrative Board is the regulator for operations, but may transfer supervision to the municipal environmental

committee. The EPA and the trade organisation Swedish Water & Wastewater Association have created guidance on the formulation of the conditions and requirements for discharges from wastewater treatment plants. Today, approximately 90% of Sweden's population is connected to approximately 2,100 municipal treatment plants. There are about 100 treatment plants with a connection of more than 20,000 people or that receive wastewater with a pollutant load corresponding to more than 20,000 PE.

The wastewater treatment plants are designed to remove oxygen-consuming substances, phosphorus and nitrogen from the wastewater. Human faeces and urine are the main sources of phosphorus and nitrogen. Close to half of all phosphorus and three quarters of the total amount of nitrogen are found in dissolved form. The treatment process can basically be divided into three treatment steps: mechanical, biological and chemical treatment.

There are no specific legal or regulatory provisions that explicitly regulate the treatment of wastewater from treatment plants with regard to the removal of pharmaceutical residues and other harmful chemicals. The plants are usually also not designed to degrade pharmaceutical residues or other hazardous substances. Pharmaceutical residues with properties hazardous to the environment therefore pass largely unaffected through the facilities and reach the aquatic environment. Harmful effects on wildlife, including intersex fish, have been observed in the receiving waters outside the facilities.

The challenges of the harmful effects of certain pharmaceuticals have been highlighted in Government Bill 2013/14:39, "Towards a toxin-free everyday environment – a platform for chemicals policy" and in Government Decision (dnr M2013/02682/Ke) on increased environmental consideration in the EU's pharmaceutical legislation. According to the Government's assessment, advanced technologies for separating and removing pharmaceutical residues and other micropollutants should be tested and evaluated in full scale no later than 2018.

Different technological solutions are available for removing pharmaceutical residues. The methods discussed most are separate treatment steps following regular treatment, consisting of oxidation, membrane filtration or adsorption to a solid material. Through the Government's budget bill for 2014, 32 million kronor in funding was granted to the Swedish Agency for Marine and Water Management over a 4-year period to promote advanced wastewater treatment. The treatment technology currently relevant for the removal of pharmaceutical residues has the positive side effect of also reducing the discharge of other harmful chemicals.

In Switzerland, advanced treatment has been introduced in wastewater treatment plants with a pollutant load corresponding to more than 80,000 PE. The costs are paid by the water service subscribers.

More about the commission

As its starting point, the EPA should utilise the research produced by the IVL Swedish Environmental Research Institute, the Royal Institute of Technology and other Swedish operators who have developed different technologies in larger sewage treatment plants and have studied the efficiency and costs of different treatment technologies.

The commission shall be carried out in close dialogue with the Swedish Agency for Marine and Water Management, the Swedish Chemicals Agency and the Swedish Medical Products Agency. The EPA should, as appropriate, consult with county councils, municipalities, municipal water supply and sewage companies, industry and other relevant authorities.

The Agency for Marine and Water Management shall contribute its expertise on the conservation, restoration and sustainable use of lakes, waterways and the sea, as well as lessons learned from the sewage treatment projects funded by the agency. The Swedish Chemicals Agency and the Swedish Medical Products Agency shall provide their expertise concerning the dangers and risks involved with chemicals.

The EPA shall report its findings to the Government Offices (Ministry of the Environment and Energy) by 1 May 2017.

On behalf of the Swedish Government

Åsa Romson

Jerker Forssell

Copy to:

Ministry of Health and Social Affairs
Ministry of Enterprise and Innovation
Ministry of Employment
Swedish Work Environment Authority
Swedish National Housing Board
Swedish Agency for Marine and Water Management
Swedish Chemicals Agency
Swedish Medical Products Agency
Swedish Association of Local Authorities and Regions
Vinnova

Annex 2 Consultation Participants and Reference Group

Consultation participants	
Swedish Agency for Marine and Water Management	Margareta Lundin Unger
Swedish Chemicals Agency	Stefan Gabring
Swedish Medical Products Agency	Kia Sahlin
Reference group	
Swedish Association of Local Authorities and Regions (SKL)	Tove Göthner
Swedish Water & Wastewater Association	Anders Finnson
Stockholm Vatten	Cajsa Wahlberg
Tekniska Verken in Linköping	Robert Sehlén
Kalix Municipality	Katarina Tano
Confederation of Swedish Enterprise	Bo Olsson, IKEM
KTH Royal Institute of Technology Div. of Industrial Biotechnology	Berndt Björleinius
Umeå University Department of Chemistry	Jerker Fick
Faculty of Engineering, Lund University Department of Chemical Engineering	Michael Cimbritz
University Of Gothenburg Institute of Biomedicine	Joakim Larsson, Lars Förlin
University of Agricultural Sciences Department of Energy and Technology	Håkan Jönsson
University of Agricultural Sciences Department of Aquatic Sciences and Assessment	Jana Weiss
Kristianstad University School of Education and Environment	Erland Björklund, Ola Svahn
Uppsala University Department of Organismal Biology	Björn Brunström
Stockholm University Baltic Sea Centre	Emma Undeman
Invited but did not participate County administrative boards Swedish National Food Agency Swedish Board of Agriculture Stockholm University, Department of Environmental Science and Analytical Chemistry (ACES) Chalmers University of Technology, Mathematical Sciences	

Annex 3 The Swedish Agency for Marine and Water Management's Ongoing Mission to Promote Advanced Wastewater Treatment

The Agency for Marine and Water Management has received 32 million kronor in funding over a 4-year period (2014-2018) to promote advanced wastewater treatment with the aim to reduce discharges of pharmaceutical residues and other micropollutants that cannot be removed in the treatment plants' current processes.⁵⁴ Eight projects focusing on different areas have been allocated funding; see Table 9. Projects 1, 2 and 7 have reported their findings, projects 4 and 8 will report findings in 2017, and projects 3, 5 and 6 will present their findings in 2018. A summary final report from the projects will be published in 2018.

Table 9. Summary of approved projects under the call for proposals for advanced treatment of pharmaceutical residues and other persistent pollutants.

Nr.	Project	Project partners	Project period
1	Pharmaceuticals and organic pollutants in the natural cycles	JTI, Stockholm County Council, LRF, Telge Nät, SLU	2014-2016
2	Pilot facility for ozone oxidation of pharmaceutical residues in sewage effluent – Tekniska Verken in Linköping	Tekniska verken i Linköping AB, IVL Swedish Environmental Research Institute	2014-2015
3	Full-scale treatment of micropollutants ("FRAM")	Kristianstad University, Malmbergs	2014-2017
4	Systems for the purification of pharmaceutical residues and other emerging substances – SystemLäk	IVL Swedish Environmental Research Institute, KTH, Stockholm Vatten, SYVAB	2014-2016
5	Treatment of persistent pollutants in wastewater ("RESVAV")	Sweden Water Research AB	2014-2017
6	Evaluation of advanced wastewater treatment in full scale	Umeå University, University of Gothenburg, SLU	2014-2016
7	Literature compilation on removal of pharmaceutical residues and other micropollutants	Michael Cimbritz et al.	2016
8	Intercalibrated pharmaceutical analysis (test comparison of analyses)		2017

⁵⁴ Govt Bill 2013/14:1, State budget proposal for 2014, category 20.

Annex 4 Summary of Estimated Quantities of Pharmaceuticals Discharged Annually from a Selection of Wastewater Treatment Plants

Concentrations of pharmaceutical residues in receiving waters downstream of the WWTPs have been calculated for a selection of Swedish WWTPs in a study by Wallberg et al. (2016).

The following table contains a summary of the substances analysed at each plant as well as the quantities (calculated at the mean concentration) discharged per year (kg/year). Purple indicates the substance that is released in the highest median amount at each facility (kg/year). Yellow indicates the pharmaceutical substances that have data available from all WWTPs and for which WWTPs all the substances were analysed.

SWEDISH ENVIRONMENTAL PROTECTION AGENCY REPORT REPORT 6766
Advanced wastewater treatment for separation and removal of pharmaceutical residues and other hazardous substances

Needs, technologies and impacts

Substance	Torsås	Bollebygd	Borlänge	Eslov	Kristinehamn	Falun	Borås	Stockholm	Uppsala	Alingsås	Göteborg	Skövde	Visby	Umeå	Östersund
Hormones															
Ethinyl estradiol (EE2)								0.3	0.1			0.02	0.02	0.2	0.04
Estradiol (E2)								0.3	0.1			0.02	0.02	0.04	0.04
Levonorgestrel	0.02	0.003	0.2	0.2	0.01	0.09	0.4	0.5	0.1	0.09	6	0.02	0.02	0.06	
Antimicrobial															
Azithromycin					0.005			1	0.2			0.02	0.008	0.03	0.1
Ciprofloxacin	0.01	0.002	0.03	0.02	0.01	0.03	0.07	2	0.2	0.02	2	0.08	0.03	0.3	0.5
Clarithromycin					0.05			3	0.8			0.07	0.007	0.7	0.04
Erythromycin					0.05			7	1			0.5	0.08	1	0.4
Fluconazole					0.1			13	5			0.6	0.3	5	0.6
Ketoconazole			0.1		0.05	0.2		3	0.5			0.1	0.08	0.3	0.1
Norfloxacin	0.004	0.002	0.03	0.02	0.01	0.03	0.07	0.5	0.1	0.02	0.7	0.02	0.02	0.06	0.1
Neurological															
Citalopram					0.005			12	5			1	0.2	2	1
Carbamazepine			2		0.4	3		58	17			3	1	8	2
Oxazepam					0.7			36	10			2	0.6	3	1
Sertraline			0.03		0.04	0.1		2	0.3			0.05	0.05	0.3	0.1
Zolpidem					0.006			0.8	0.3			0.02	0.008	0.06	0.03
Analgesic															
Diclofenac	0.2	0.1	1	0.6	0.8	1	4	37	29	0.5	25	2	0.7	5	3
Ibuprofen	0.2	0.02	0.5	0.4	0.2	3	3	9	2	0.3	11	0.4	0.3	1	1
Ketoprofen	0.1	0.09	1	0.4	0.01	0.3	2	3	2	0.8	54	0.5	0.3	2	2
Codeine					0.1			8	9			0.8	0.6	6	3
Naproxen	0.2	0.08	1	0.8	0.01	0.4	2	4	1	1	60	0.8	0.5	3	8
Paracetamol					0.1			8	0.7			0.5	0.5	1	0.4
Tramadol					1			83	40			5	1	15	4
Cardiovascular															
Eprosartan					0.005			11	1			0.09	0.03	3	0.02
Flecainide					0.3			12	3			0.3	0.2	1	0.4
Metoprolol					2			126	27			5	4	19	8

Annex 5 Technologies for Advanced Treatment and Their Advantages and Disadvantages

Ozonation (O₃)

Ozonation (O₃) is an oxidative treatment in which different substances are oxidized with ozone, either through a direct chemical reaction with the ozone molecule, or indirectly after the formation of hydroxyl radicals, which break down the specific chemical bonds in the substance. The most common application of ozonation for the degradation of micropollutants is as a final polishing step following the main treatment process. The degradation rate of persistent organic pollutants depends on factors like ozone dose, but is also influenced by the concentrations of other organic compounds in the treated effluent. Because ozone is a reactive gas, it cannot be compressed and stored easily. This is why it is generated on site.

One advantage of ozonation is that it is a versatile technology that provides the capability to control ozone doses and contact times. Also, the same removal efficiency can be expected over the lifetime of the treatment plant. Ozonation requires active monitoring and control to obtain an optimised process, and the technologies for this are under development. This is also an important consideration for reducing operating costs, since the energy consumption is high for ozone generation. One disadvantage of ozonation is the formation of transformation products that can have ecotoxicological effects that are difficult to quantify. This technology therefore requires post-treatment (ideally, biological) in order to minimise the risks of degradation products.

- + Extensive experience of water ozonation (primarily drinking water) and sludge (foam, slurry).
- + Several full-scale installations of additional ozone treatment for oxidizing pharmaceutical residues and other organic pollutants.
- + At sufficiently high doses, ozonation can disinfect water.
- + Flexible installation is possible, with control of different ozone doses and contact times.
- + Same removal efficiency over the facility's service life can be expected.
- + Relatively low total cost (SEK/m³) compared with other technologies.
- + Standard technology with many providers in the market.
- The ozone dose required varies from substance to substance and depends on the water composition, which varies over time.
- Requires monitoring and control for optimised operation, and measurement equipment is under development.
- Effective treatment requires a low amount of organic material in the water to be treated.

- The formation of transformation products, some stable and others biodegradable, have potential ecotoxicological effects that are difficult to quantify. Might pose an occupational health and safety risk, which has not yet been studied in detail.
- Requires post-treatment (ideally, biological) to minimise the risks of degradation products.
- High energy use during ozonation and the manufacture of liquid oxygen (same level as for activated carbon if the production and regeneration of activated carbon are included).
- Occupational health and safety risks when handling ozone (fire risk, health hazard).
- To minimise the risk of ozone leakage, materials and equipment in an ozonation step must be ozone-resistant, and a security system must be installed (leak alarm, gas alarm, ozone destructor).
- Risk of fire and explosion when handling liquid oxygen.

Granular activated carbon (GAC)

The basic principle of granulated activated carbon (GAC) is the adsorption of contaminants on the active carbon surface. When using GAC, the carbon is placed in filter beds in a separate treatment step. When the carbon has become saturated (adsorption surfaces are unavailable), the carbon needs to be replaced by new carbon to maintain the removal efficiency. The spent carbon is regenerated and can then be used again. This technology has been used for a long time in various water treatment applications, and exhibits a good removal rate for pharmaceutical residues. Obtaining an effective treatment requires minimising the pollutant level and the concentration of suspended solids in the water to be treated in order to maximise the separation of pharmaceutical residues and other hazardous substances and to increase the life of the carbon. This method has relatively low energy consumption during operation, but has high resource consumption during the production and regeneration of the activated carbon.

- + Has been used a long time in various water treatment applications.
- + Good removal efficiency for pharmaceutical residues.
- + No size limitations for the GAC filter, and suitable for both large and small facilities.
- + Biofilm on the filter causes biological decomposition of adsorbed compounds and other organic pollutants and nutrients (see also the section on BAF below).
- + Space-efficient, if it is possible to transform existing sand filters to GAC filters.
- + No residues that affect, for example, sludge quality, and pollutants are treated during regeneration.
- + Good workplace health and safety.
- Risk of clogging, and requires regular backwashing to avoid hydraulic limitations.

- Other pollutants than those intended compete for adsorption surfaces – good to minimise the concentration of suspended solids in the water to be treated in GAC.
- High energy and resource consumption during the production and regeneration of carbon.
- 10-20% carbon losses at regeneration.
- No commercial production or regeneration of activated carbon in Sweden, so fossil fuels are used more often for energy production as well as increased transport.
- Uncertainty surrounding carbon requirements and carbon life, which greatly affects finances.

Powdered activated carbon (PAC)

Treatment with activated carbon can also be done with powdered activated carbon (PAC). This treatment process is also based on adsorption of contaminants on the carbon, where the carbon is added to the main process in the biological stage before any final filtering in a sand filter or in an additional treatment step. Unlike GAC, PAC is removed along with the sludge if it is added to the main process and thus not regenerated. When PAC is added to the biological treatment step, contact time increases. Yet there are more pollutants competing for available adsorption surfaces on the carbon, reducing the carbon's effect on the removal of pharmaceutical residues.

One advantage of PAC is that it only requires the installation of storage and dosing equipment when it is being added to the main process. Also, the dosage can be adjusted according to the influent load. The technology requires an effective separation step in order not to discharge the PAC to receiving waters. In certain applications the PAC dosage can result in contamination of the sewage sludge, which limits the possibilities of using it as fertiliser in agricultural applications.

- + Available operating experience of adding PAC to the main process at full-scale facilities.
- + No fixed size limitations for the facility.
- + During internal recirculation and increased contact time, PAC particles act as carriers and thus help to reduce pollutants other than pharmaceutical residues in the wastewater.
- + PAC for the main process requires only the installation of storage and dosing devices.
- + Lower cost for PAC than GAC if regenerated GAC can be used like PAC.
- + Low energy use during operation when dosing in the main process (assumes that UF is not required for separation).
- Requires an effective separation step to avoid discharging PAC and toxic pollutants to receiving waters, and often requires more than post-sedimentation.

- For some of the applications, can produce contaminated sludge as a by-product from the WWTP.
- Limited experience of separate PAC handling (which is necessary if sludge quality is not to be adversely affected).
- Creates a corrosive and abrasive⁵⁵ environment that can cause material wear, so the equipment should be selected carefully.
- Some uncertainty surrounding carbon requirements for achieving an extensive treatment of pharmaceutical residues.
- High energy consumption to produce or regenerate PAC.
- Health and safety problems due to dust formation. Can be reduced by handling PAC in closed systems, with inert gas in order to reduce the risk of fire and explosion.

Biologically active filtration (BAF)

Biologically active filtration (BAF) uses standard filters (such as sand filters or activated carbon) which, in addition to the filtering effect, also involve biological activity that breaks down certain pollutants. Even a wetland can be considered a biologically active filter. To reduce the load of pollutants other than the ones designated for treatment, the placement of the BAF should be done as a final treatment step. The filter is backwashed regularly, and the backwash water is usually returned to the biological treatment step in the WWTP.

One advantage of this technology is that it is based on traditional sand filters or GAC systems, which are established technologies at WWTPs. GAC as a filter media is advantageous because it provides adsorption of pollutants and a high specific surface area where microorganisms attach and pharmaceutical residues can be separated. A disadvantage is that the biology requires a few days up to a few weeks of start-up time, and can increase clogging and the need for backwashing with potential hydraulic limitations over the filter. Many micropollutants are degraded either in a biofilm system or an activated sludge system, which is why BAF with activated carbon offers the highest removal efficiency.

- + Is based on a traditional sand or GAC system, common technology with several technology providers.
- + Can be applied at WWTPs of all sizes.
- + Requires in itself no regular replacement of filter media when pollutants are degraded. However, a GAC filter becomes less efficient over time as the adsorptive capacity decreases, after which regeneration or replacement of the filter is required.
- + GAC as a filter medium is advantageous because it provides adsorption of pollutants and a high specific surface area where microorganisms attach.
- + Provides increased removal of nutrients.
- + Residue created only during filter replacement.
- + Provides increased degradation of organic pollutants.

⁵⁵ Technical designation for wear/abrasion.

- + The return of pharmaceutical residues to the main treatment allows for enhanced biodegradation.
- + Low energy requirements.
- To reduce the levels of most pharmaceutical substances, however, requires other, or additional, treatment steps unless activated carbon is used as a filter material.
- The biology requires longer contact times (>10 min.) and start-up times (can take days or weeks). However, using GAC as a filter material offers removal efficiency from the outset.
- Hydraulic capacity problems due to microbial growth and filter action require regular backwashing to prevent potential operational problems.
- Difficult to control removal efficiency with respect to load in real time.
- Extensive experience (>2 years) for wastewater treatment with BAF not available.

Ultrafiltration/Membrane Bioreactor

Ultrafiltration (UF) is a physical treatment method that uses a membrane to filter particles. Depending on the membrane selection, particles and even larger soluble molecules can be separated down to about 10 nm (Baresel m.fl., 2017). UF integrated in the main treatment at a WWTP as a membrane bioreactor (MBR) is available in full scale, but UF is more unusual as a separate treatment step. UF is also used as a microbiological barrier for treating drinking water.

An important operational consideration when using UF is that the membrane surfaces become coated over time. This is known as fouling, and requires the use of chemicals to clean the membranes. In addition to chemicals, UF results in higher energy consumption, both during operation and the production of the membrane.

One advantage of ultrafiltration technology is that it acts as a physical barrier to the receiving waters and for any subsequent treatment steps to separate pharmaceutical residues (ozonation or activated carbon). It has a good treatment effect on particulate matter, microplastics, pathogens and bacteria and thus also on multidrug-resistant bacteria, but not on the development of resistance in general. A disadvantage to this technology is that it does not remove substances that are soluble in the aqueous phase, which is why most pharmaceutical residues are not separated using UF. This technology is considered to be generally more expensive than other technologies. But as advancements in membrane production take place, costs continue to decline (Baresel et al., 2017). For applications like MBR, the technology can offer a space-efficient solution that replaces the need for post-sedimentation in an activated sludge process, an advantage at WWTPs that lack capacity.

In summary, UF has limited removal efficiency for pharmaceutical residues and only shows potential as an additional treatment step for particulate matter or in

combination with other treatment technologies such as activated carbon or ozonation.

- + Space-saving – Replaces post-sedimentation in activated sludge processes.
- + Acts as a physical barrier to receiving waters, and for any subsequent treatment steps.
- + Removes particles down to 0.1 µm (depending on size), including microplastics, viruses and antibiotics resistance.
- Fouling of the membrane surface – Requires energy and chemicals.
- Does not treat non-particle-bound pollutants, which means that most pharmaceutical residues are not removed with UF.
- Expensive technology.
- Energy-consuming process (for the production of chemicals and membranes as well as operation).
- Chemicals handling – A health and safety issue and an environmental issue.
- Concentrates are formed as a waste product.

The combination of powdered activated carbon and ultrafiltration (PAC-UF)

The combination of powdered activated carbon (PAC) and ultrafiltration (UF) can be used as an integrated or additional treatment step at existing WWTPs. The integrated treatment consists of an MBR process in which PAC is added to the MBR reactor. The contact time in PAC-UF is determined by the reactor volume and PAC/sludge retention time. A combination of PAC and UF meets the requirements of an effective separation system with activated carbon that removes pollutants through adsorption, and ultrafiltration that separates and removes all pollutants larger than the membrane's pore diameter, including any residues of contaminated, powdered activated carbon. One disadvantage of using activated carbon in powder form is that it hinders the regeneration of the activated carbon. For a description of PAC and UF, see their respective sections.

Using PAC-UF as a separate treatment step after main treatment requires separate handling of the resulting sludge (retentate) if it is not to affect the quality of the sludge produced at the WWTP. If, instead, PAC is added to an MBR reactor integrated in the treatment process, the existing sludge disposal will have a negative impact on the sludge quality as a result.

- + A high PAC retention time in the process can increase carbon capacity.
- + Through ultrafiltration, all pollutants that are larger than the membrane's pore size are removed.
- + Flexibility in adaptation to different load via the PAC dosage.
- + Biofilm on the activated carbon can increase the removal of organic pollutants.
- + Ultrafiltration provides an effective separation and removal of bacteria and viruses, and antibiotics are removed with PAC. The technology combination inhibits the development of antibiotic resistance in receiving waters.

- To obtain a good solution for managing the concentrate, two-step solutions might be needed for PAC-UF as additional treatment steps.
- PAC regeneration is not possible for the PAC-MBR option (mixed with sludge).
- For some of the applications, PAC can produce contaminated sludge as a by-product from the WWTP.
- PAC can create a corrosive and abrasive environment, and this must be taken into account when acquiring the membrane.

The combination of ozonation and biologically active filtration (with granulated activated carbon)

This technology combination consists of ozonation and biological post-polishing with granulated activated carbon (GAC) as a filter material. It provides a multi-step treatment using both oxidative and biological degradation as well as adsorption of pollutants and by-products formed during ozonation. Elevated concentrations of oxygen from ozonation promote a biodegradation of pollutants in addition to adsorption, as long as they do not become too high, which can interfere with the biology. This technology combination has been tested both with and without microfiltration as pre-treatment prior to ozonation (Baresel et al., 2017), and provides an almost complete removal of pharmaceutical residues and other impurities, except for microplastics. See also section 5.2 (Baresel et al., 2017). The ozonation step provides dynamic control of the removal efficiency. At high concentrations of suspended solids, additional filtering is recommended to remove particles larger than 10 µm in order to minimise the amount of disruptive substances that consume the ozone or BAF capacity (Baresel et al., 2017).

- + Removes all pharmaceutical substances.
- + Elevated concentrations of oxygen from ozonation promote a biodegradation of pollutants in addition to adsorption.
- + Can break down or adsorb residues formed during ozonation.
- + Can achieve water sanitisation (but might require higher ozone doses).
- + Reduces the risk of multidrug-resistant bacteria through the removal of bacteria and degradation or adsorption of antibiotics.
- + Treatment can be controlled based on different load and treatment goals.
- + Familiar technologies that are offered by several technology providers.
- + The activated carbon can be regenerated.
- + Cost-effective technology combination (compare the cost-benefit analysis).
- + Applicable for all WWTP sizes.
- + Almost complete removal of other pollutants (except microplastics).
- + Extra treatment of nutrients.
- + Lower ozone doses for the same treatment effect than with the application of ozonation alone.
- + Carbon exchange is needed less frequently with previous ozonation compared with systems that only use activated carbon filtration.

- At high levels of residual ozone, the biology in the biological filter can be disturbed.
- Even during application as a final treatment step, it requires extra filtering to remove particles larger than 10 µm.
- High energy use in connection with ozonation and the production of liquid oxygen and activated carbon. However, there are indications that this technology is more energy efficient than each treatment technology alone.
- Health and safety risks when handling the ozone (see section 5.3).

The combination of ultrafiltration and biologically active filtration (with granulated activated carbon)

This system combines membrane separation with a biological and adsorptive filter. The membrane can be integrated in the WWTP. In this case, the system is called a membrane bioreactor (MBR) with subsequent biological and adsorptive filter (BAF (GAC)). Because the activated carbon is not added to the membrane stage, this reduces the load on the membrane and helps avoid a negative impact on the sludge quality compared with the powdered activated carbon (PAC) system. The removal efficiency when using ultrafiltration (UF) followed by BAF (GAC) is more than the total of the removal efficiency of any one system alone, because the load on the BAF system decreases thanks to the previous UF step. The removal efficiency of BAF is determined entirely by the biology and adsorption capability of the filter material (Baresel et al., 2017). Moreover, the return of backwash waters to the biological treatment step in the WWTP provides additional biodegradation (Baresel et al., 2017). The technology combination of UF (which removes microplastics and multidrug-resistant bacteria) and activated carbon (which separates pharmaceutical residues, including antibiotics) can prevent a possible multidrug resistance downstream of the WWTP (Baresel et al., 2017).

At Hammarby Sjöstadswerk, testing has been ongoing for several years using MBR followed by BAF (GAC). In Kalmar, pilot tests are in progress as of 2017 using ultrafiltration followed by granular activated carbon. There are several providers of membrane systems and of filters with activated carbon, but the combination is not yet a commercial product (Baresel et al., 2017).

- + Higher removal efficiency when the load of particles and organic material decreases at the GAC system.
- + The return of pharmaceutical residues to the main treatment allows for enhanced biodegradation.
- + Simpler membranes can be used, and the purchase and operation of the membranes thus becomes less expensive than, for example, PAC-UF.
- + Removal of particle-bound contaminants, including microplastics.
- + Prevents the development of multi-resistance downstream of WWTPs through the removal of bacteria and pathogens with UF, and adsorption of antibiotics in BAF (GAC).

- + MBR helps to achieve a more powerful, space-efficient biological treatment compared with conventional biological treatment (section 3.1.1 in Baresel et al. (2017)).
- Chemicals are required to clean the membranes.
- High energy use to produce the membrane and activated carbon.
- Concentrates are formed as a waste product. In this application, this is managed in an integrated way in the process by being pumped back into the main treatment.

Annex 6 Interviews with Two Local Authorities on Introducing Advanced Treatment

Interviews were conducted with representatives from the two municipalities that are in the process of introducing advanced treatment in order to remove pharmaceutical residues at WWTPs.

Tekniska Verken, Linköping⁵⁶

At Tekniska Verken in Linköping, a complementary ozonation step is under construction at Nykvarnsverket in Linköping. The treatment plant is dimensioned for 235,000 PE, and is owned and run by Tekniska Verken in Linköping ("Tv AB"). They have 900 employees, of whom roughly 100 are working with water and sewage services. A pilot project was completed in 2014-2015 (Sehlén et al., 2015) whose primary purpose was to investigate ozone treatment as an alternative to pharmaceutical removal at Nykvarnsverket in Linköping and to provide reliable technical background material for a decision on a full-scale process solution. The total time from concept to facility commissioning has taken roughly four years.

The total budget for the project is 23-25 million kronor. Of this, approximately 11 million is estimated for the actual treatment technology, 9 million for groundwork, blast clearing and installation, 2 million for building and 2-3 million for other items such as design, instrumentation, etc. The cost of the new electrical substation was not included in the investment budget because it was necessary prior to the project (Baresel et al., 2017). The implementation of advanced treatment will result in a total annual cost increase of about 4 million kronor/year, of which about 2 million per year will be an increase in operating costs. This is roughly equivalent to a 5% increase in today's operational costs.

According to Tekniska Verken, the main drivers leading to the decision to introduce advanced treatment were: management's desire to *be a front-runner* and help *benefit business, the environment and society at large*, the *commitment and ability* of employees to do the development work, *access to resources* and the assessment that the *costs* were reasonable *in relation to the benefits to society* of avoiding environmental risks (i.e., for the receiving waters).

Desire to be a front-runner

There is a willingness from management, grounded in Tekniska Verken's stated objectives, to operate in an area that benefits the company financially but also from an environmental and a socio-economic perspective ('business, the environment,

⁵⁶ Lövsén (2017).

and society at large'). Tekniska Verken has a vision to build the world's most resource-efficient region, and being 'driven' is a core value of its business.

Commitment and ability to do the development

Tekniska Verken highlights the importance of dedicated employees who want to help realise management's vision while understanding that it must have the resources and space to do the development work. The organisation has assessed that it has sufficient operational and maintenance staff, but that the staff will require further training. Tekniska Verken believes that the treatment plant must be large enough to ensure the availability of resources when the new technology is implemented.

Costs versus benefits

When the investment decision was taken, Tekniska Verken performed an analysis that weighed the investment and operational costs against the benefits. A risk analysis based on the EC/PNEC factor⁵⁷ in the receiving water body (the Stångån river) was completed (Sehlén et al., 2015), and shows that the concentrations of several pharmaceutical residues, as measured in the effluent, risk negatively impacting the Stångån. The estimated cost – approximately SEK 25 million – has been assessed to be justifiable considering the risk to the environment.

Financial considerations

Tekniska Verken is not planning to increase the municipal water and sewage fee. However, it has implemented efficiency measures (and will continue to do so) within water and sewage operations to compensate for the increased operating costs of the ozonation. The Swedish Agency for Marine and Water Management has funded a feasibility study, and Tekniska Verken hopes to receive EU funding for an expanded programme for monitoring and operation optimisation. But these financial contributions have not been crucial to implementing the initiative. The pilot project was instrumental for gaining experience and onboarding operational staff to the project, and for finding the site-specific solution with the ozonation step. In this case, implementation took place after notification to the County Administrative Board, which consequently has reduced administrative costs. Tekniska Verken's environmental permit for Nykvarnsverket is relatively new.

Kalmar Vatten⁵⁸

Kalmar Vatten plans on building a new WWTP to replace its existing one. In the spring of 2016, the municipal council took a strategic decision and a programme document is now under development. The schedule for the new WWTP is to start building in 2019 and be fully operational by 2023. The strategic decision includes

⁵⁷ The EC/PNEC factor is the ratio between the Environmental Concentration (EC) of the effluent and the Predicted No Effect Concentration (PNEC) (Sehlén et al., 2015).

⁵⁸ Ullman and Zhao (2017).

an investment in a UF facility, but a decision on the introduction of pharmaceutical treatment has not yet been taken.

A multi-criteria analysis⁵⁹ was performed in 2012 as a basis for designing the new WWTP. It identified the following criteria:

1. Discharge to water and contamination
2. Reliable and robust WWTP (relatively small staff and no expansion capacity at the WWTP)
3. Flexibility for future expansion
4. Future flexibility with respect to tougher regulatory requirements (on nitrogen, phosphorus, pharmaceuticals)

Pilot trials were conducted in 2015-2016 with the purpose of using ultrafiltration to remove microplastics. Since then, an additional treatment step using activated carbon was added in order to evaluate the separation and removal of pharmaceutical residues and other organic micropollutants. This pilot project will last for one year and will end in February 2018.

According to Kalmar Vatten, the main drivers behind development efforts to introduce advanced treatment were: management's desire *to be a front-runner*, the *commitment and ability* of employees to carry out development work, a *political interest* in the environmental risks, and the *expectation of future legislation* on the treatment of pharmaceutical residues. The *precautionary principle* has also been a key driver more important than the cost-benefit results.

Desire to be a front-runner

There is a willingness from management, guided by Kalmar Vatten's vision, to become the best water and sewage company. This long-term vision has allowed for pilot tests to be conducted that combine ultrafiltration with additional treatment steps using activated carbon.

Political interest

When Kalmar Vatten began its selection process for a system for the new WWTP, the microplastics issue emerged. Also, public debate brought to light the risk of negative environmental impacts from the discharge of pharmaceutical residues. This sparked the interest of politicians and contributed to the decisions that were taken regarding advanced treatment.

Expected stricter treatment requirements

Among the considerations of the multi-criteria analysis conducted in 2012 were discharges into the water, contamination risks and the need for a flexible facility that could meet future treatment requirements. A relatively large study that

⁵⁹ Urban Water, 2012.

specifically focused on future treatment requirements was also conducted, and is continuously updated as global developments are monitored.

The precautionary principle

In its strategic decision, Kalmar Vatten included the investment in ultrafiltration on the grounds that it is justifiable to remove microplastics and reduce the risk of the spread of antibiotic-resistant bacteria from a precautionary perspective. However, the cost-benefit justification for introducing pharmaceutical separation and removal was not considered strong enough considering the properties of the receiving waters.

Financial considerations

No financing decision has been taken with regard to covering the extra cost for additional treatment of the pharmaceutical residues. Kalmar Vatten estimates that funding for advanced treatment becomes difficult to justify if the requirements of the receiving waters and/or legal requirements cannot be demonstrated. This is because the cost of such a treatment step is assessed to be quite high.

Advanced wastewater treatment for separation and removal of pharmaceutical residues and other hazardous substances

REPORT 6803

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Needs, technologies and impacts

As commissioned by the government of Sweden, the Swedish Environmental Protection Agency (EPA) hereby presents its report outlining the prerequisites for using advanced treatment at wastewater treatment plants to separate and remove pharmaceutical residues. The report analyses the need for advanced treatment, the technical solutions available including their advantages and disadvantages, and other implications of the use of advanced treatment.

The Swedish EPA has determined a need to introduce advanced treatment for pharmaceutical residues in wastewater. An additional benefit of such treatment is that it would also include the treatment of other hazardous substances. The need is justified broadly based on the risk of long-term effects from the discharge of pharmaceutical residues to the aquatic environment.

The Swedish EPA further maintains that technologies are available for advanced treatment that can be implemented as a complement to existing treatment steps, and that economies of scale can be gained at larger plants.

Limiting the discharge of pharmaceutical residues into the environment requires a wide range of measures throughout the chain, from the development of new drugs, their manufacture and use through to the handling of residues and their release into the environment. This report represents a step towards the implementation of advanced treatment at wastewater treatment plants. The need to introduce advanced treatment varies, and we do not currently know how many plants or which ones should be prioritised. This need should be clarified. Also, the necessary governance and controls must be determined for implementing advanced treatment where the need is greatest, in a way that is socioeconomically efficient and fit for purpose.

