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Review paper

Sanitary Systems: Challenges for Innovation

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ABSTRACT

Global society is confronted with various challenges: climate change should be mitigated, and society should adapt to the impacts of climate change, resources will become scarcer and hence resources should be used more efficiently and recovered after use, the growing world population and its growing wealth create unprecedented emissions of pollutants, threatening public health, wildlife and biodiversity. This paper provides an overview of the challenges and risks for sewage systems, next to some opportunities and chances that these developments pose. Some of the challenges are emerging from climate change and resource scarcity, others come from the challenges emerging from stricter regulation of emissions. It also presents risks and threats from within the system, next to external influences which may affect the surroundings of the sewage systems. It finally reflects on barriers to respond to these challenges.

KEYWORDS

Modern sanitary systems, Climate change adaptation and mitigation, Resource recovery, Sewage effluents, Emissions, Lock in, Load factor.

INTRODUCTION

Sanitary systems emerged in the 19th century. They were a response to a new threat: cholera. The 1817-1824 Asia and Middle East cholera epidemic had drawn attention to this disease. Europe was first seriously struck by cholera in 1830-1832, but the disease returned frequently. It posed the main reason to take sanitary measures [1, 2]. After the successful London sewage system was constructed between 1859 and 1865, many sewage systems emerged in Europe [3-5].

Some cities introduced dry sucking systems that allowed agricultural use of the collected excrements [6, 7]. However, the introduction of a new invention, 'water

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closets', led to 'flushing' and diluted sewage that could not be used as fertiliser. Where to put the diluted dirt? Coastal cities created outlets to the sea. Inland cities, often first spoiled their rivers before starting to treat sewage by sewage farming. Sewage farming took much land and raised protests [8, 9] but agricultural use of sewage is still practiced at large scale, especially in developing nations [10].

Sewage treatment was successfully introduced in the Interbellum. In the second half of the 20th century, sewage systems further diffused, and sewage treatment became standard in the industrialised world. Stricter environmental regulations and the introduction of various household chemicals [11, 12] created new problems. By the end of the 20th century, agricultural use of sewage sludge was often terminated to prevent chemical- and bio-hazards. However, this also disrupted the mineral cycle of the food chain as trace minerals ended in the incinerator instead of being used as fertiliser.

The developments in the waste water system can be defined in different stages of treatment, starting with the primary stage of mechanical treatment for simple sedimentation. The activated sludge treatment can be defined as the secondary treatment. Additional water treatment and processing and disposal of the sludge is the tertiary treatment [13]. This paper focuses on analysing today's new challenges for sanitary systems, which mainly can be found in the tertiary treatment process:

- Climate change;
  - Mitigation of climate change requires: A far increased energy performance of sewage systems, i.e., becoming net energy producing, and reduced emissions of greenhouse gases;
  - Sewage systems should be adapted to the impacts of climate change;
- Resource scarcity: The world is running out of resources. How can resources be recovered by sewage systems? (e.g. phosphates, precious metals, urea, alginates, clean water);
- Risks for the environment. Sewage systems pose a risk for their environment by various forms of malfunctioning: Causes could be the internal safety (e.g. for gas explosions), external safety (for sabotage), disturbance of sanitary performance, criminal use, and limited treatment due to cost efficiency.

The paper analyses the current challenges for sewage systems and reflects on barriers for innovation that are caused by sewage systems' historic lock-in.

MITIGATION OF CLIMATE CHANGE AND ADAPTATION TO ITS IMPACTS: THE CHALLENGE FOR SANITARY SYSTEMS

What are the options for mitigating climate change impacts caused by sewage systems and Waste Water Treatment Plants (WWTP's)? On multiple levels of operation there are aspects which can affect climate change. There are greenhouse gasses emitted, most important for the waste water cycle are methane (CH_4) and nitrous oxide (N_2O), emitted to air when treating the waste water. Contaminants in the effluents of a WWTP might disturb natural processes, which in turn might cause additional greenhouse gas emissions but might also fixate carbon dioxide (CO_2) as organic matter [14]. Table 1 shows the climate impact of waste water treatment in the Netherlands in tonnes CO_2 equivalent as an example of how much gasses are emitted and energy is used.

Additional water treatment might require more energy. Hence, there might be a trade-off between improved treatment and energy consumption [15].

The extraction of heat from a waste water system or the use of biogas produced by the waste water treatment plant might help mitigating climate change.

Direct CO_2 emissions due to the oxidation of the organic materials in WWTP's and sewage systems are not taken into account, as they are a part of the short cycle closed loop from 'plants (-meat) -food-excrements-CO_2-plants'. However, CO_2 emissions from fossil fuels used for pumps in the sewage system and the WWTP itself are important [16].

Greenhouse gas emission reduction

N_2O and CH_4 are the two main greenhouse gasses produced in a WWTP. N_2O is formed in the process of nitrification. Various process parameters influence the nitrification process, like the concentration of organic materials in the sewage, the concentration of oxygen, temperature and the concentration of ammonium [17].

In 2008, the total Global Warming Potential of the water cycle (drinking water production, sanitation and waste water treatment) was analysed.

Table 1. Climate impact of waste water treatment in the Netherlands in tonnes CO_2 equivalent [18], sewage collection systems not included, treating domestic sewage took 40 kg CO_2 equivalent per person in 2006, however, the performance of WWTP's has improved afterwards [19]

	Unit	Number	Conversion	[t CO_2]
Sewage	[m^3]	1,853,577.000		
Organics	Inhabitant equivalents	26,796,091		
	Energy consumption			
Electricity	[kWh]	544,100,000	0.59 kg/kWh	321,020
CH_4	[m^3]	28,882,000	1.8 kg/m^3	51,990
Sludge processing				102,100
	Direct emissions			
CH_4	[kg]	8,400,790	21 kg/kg CH_4	176,417
N_2O	[kg]	1,166,715	310 kg/kg N_20	361,682
Methane flared (methane not incinerated)	[kg]	20,810	1 kg/kg CH_4	21
	Indirect emissions			
Materials for treatment				35,628
Office heating				30,495
Transport				13,965
Total				1,093,326
Per inhabitant equivalent of waste water				0.041

Waste Water Treatment Plant biogas production and consumption

Besides clean effluent, the WWTP's final product is sewage sludge: this sludge mainly consists of the biomass that has grown on the organics that were present in the sewage. This sludge might be digested in an anaerobic digester, by which biogas is produced [20].

Biogas is often used at the WWTP site, for generating process heat or for generating combined heat and power [21]. Biogas might also be cleaned, upgraded to reach a specific caloric value, and inject it into the gas grid or it might be used as a transport fuel [22].

Biogas is produced in an anaerobic sludge digestion process. During a retention time of around 20 days, microorganisms break down part of the organic matter that is contained in the sludge and produce biogas, which is composed of CH_4, CO_2 and trace gases. The raw biogas needs to be dried and hydrogen sulphide and other trace substances removed in order to obtain a good combustible gas. For biogas produced from sewage sludge (as well as from landfills), removal of siloxanes is required as siloxanes create much wear in combustion equipment [23]. Cleaning biogas may be carried out by:

- Water scrubbing (a cheap process at larger scale);
- Pressure swing absorption (using differences in absorption under different pressures);
- Membrane filtration [23].

Biogas might also be cleaned and used as transport fuel. Experiments have been carried out in several cities [24, 25]. In Sweden, a nationwide network of biogas fuelling stations has been created [26, 27].

By anaerobic digestion the volume of the sludge is reduced, which is advantageous if the sludge should be transported [28]. The remaining sludge still contains considerable water.

If waste heat is available, e.g. in a cement plant, this might be used to dewater the sludge further. After incineration the ashes contain valuable minerals, like phosphates, which might be recycled [29].

Extracting heat from waste water

Waste water that leaves dwellings by the sewage pipe has increased in temperature during recent decades. This effect is caused by several factors:

- Dwellings are more and better insulated. Even in the colder climate zones, high insulating walls and -glazing keep dwellings rather warm at night (~15 °C). This implies that the flushing water of toilets heats up to 15-20 °C;
- Hot water is easily available throughout the house and so it is used increasingly;
- Personal hygiene has become more important. As a consequence, people shower more, or take baths. The washing machine is used more often to wash laundry and clothes. The water heats up the sewers.

By these trends, the water that enters the sewers might be 23-26 °C [30]. Sewage is the largest factor in heat loss of well insulated buildings [31]. Moreover, as more and more sewage systems are separated (waste water/precipitation), the warmer water is less diluted by precipitation. The heat that enters the sewage system will be lost in longer distance sewage pipe transport. It is therefore of interest to ‘harvest’ this heat locally [32].

WWTP’s treat waste water at about 35 °C. Their effluents are therefore even a better and larger source of heat. The heat of effluents might be harmful to the ecosystems of the receiving water bodies, as water with elevated temperatures contains less oxygen, and diseases will develop faster [33], thermal emissions are therefore regulated, and utilising the heat will diminish energy consumption and prevent environmental harm [34].

Depending on local conditions, energy consumption for heating can be reduced significantly by using heat from sewage mains. Using other local sources of heat might be facilitated by the systems to recover heat from sewage, which can lead to additional reductions. Heat pumps are a key technology to recover this heat [31, 35, 36]. Heat recovery of WWTP’s also has an ecological advantage: uncontrolled discharges of WWTP effluents might harm wildlife by thermal shock. Especially during summer heat waves, effluents and urban run-off might strongly influence river temperatures creating a thermal shock for fishes [37]. The EU implemented regulations on thermal releases in 2006: thermal releases are forbidden if the water temperature exceeds 28 °C (Cyprinid waters) or 21.5 °C (Salmonid waters). Moreover, heating of waters by discharges might not exceed 3 °C (Cyprinid waters) or 1.5 °C (Salmonid waters) [38]. The US Environmental Protection Agency formulated similar guidelines for Salmonid waters in the US North West [39].

Adaptation to climate change

Due to climate change, many regions will face moments of extreme precipitation. The intensity and frequency will be higher than known today [40]. During a short period of time large volumes of water might enter combined precipitation/sewage systems which require a quick reaction [41]. The cluster of showers that hit Copenhagen in July 2011 flooded the city and created unprecedented damages [42]. Short- and long-term measures should be applied to cope with extreme precipitation. For the long-term, water storage options might be created like retention basins, infiltration, and of course expansion of the sewage systems’ capacity.

The main issue of extreme precipitation is the fact that it hardly has time to enter the soil. In recent decades, the paved areas in cities areas have grown in size, which accelerates the run off, but creates problems for combined sewage systems. Slowing down the water from entering sewage systems by making green roofs [43], diminishing (or making permeable) pavement in gardens and parking lots [44], and creating water storage [45] could help preventing problems during extreme rainfall. An interesting short-term measurement is temporary water barriers. These barriers have to be able to be rapidly applied. It can be anything from the classical sandbags to new floating barriers which pop up when the water rises [36].

The success of all of these measures is depending on when and where the extreme precipitation will fall. As climate change implies, a structural change in rainfall patterns, historic data are of little use. Statistical model analysis of extreme precipitation events is still of limited value and uncertainties are large. Elaborate models require too much computing time to be helpful for emergency warnings. For example, the Royal Dutch Meteorological Institute (KNMI) uses a so called 'Harmonie-Arome model, which is designed especially for short range weather forecasts [46], but its rendering takes too much time to calculate entire scenarios[†].

The impacts of floods or water nuisances in a city will increase in the future. As cities will get more crowded, with more elaborate infrastructures, water might create more damage, and direct as well as indirect economic losses [47]. Flooding also had consequences for the sewage system and WWTP's. They will release raw sewage which creates public health threats [48, 49].

In large parts of the world (California, Spain, Northern Africa, Middle East, Australia) lack of precipitation is a main impact of climate change [50]. Especially in those areas, using less water for sanitation might be important [51]. Filtering effluents until they reach drinking water quality might be an interesting option under those conditions [52].

RESOURCE SCARCITY AND THE CIRCULAR ECONOMY: CUTTING EMISSIONS AND BOOSTING RAW MATERIALS RECOVERY

Sewage systems have been created for sanitation of cities. As sewage systems initially just transferred the sewage out of the city, without any cleaning, the same system was also used to get rid of precipitation. Moreover, any substance was allowed to enter the system. After WWTP's were added to sewage systems, the situation changed completely:

- Some chemicals could harm sewage treatment and were to be kept out of sewage systems;
- Sewage treatment had a limited capacity, so rainwater was not to be fed into the sewage treatment as the WWTP could not process the larger volumes.

Many sewage systems remained combined precipitation/sewage systems, as change was expensive. Hence, during heavy rainfall, the system collected too much water for the capacity of the WWTP. Therefore, 'overflows' were introduced by which raw (untreated) sewage could be discharged. In sewage systems that are still largely 'combined' systems, emissions of untreated sewage still occur regularly. However, during heavy rainfall, the sewage is rather diluted. The impacts are similar to 'no sewage treatment'. Studies showed that there is a strong relation between outbreaks of water-borne diseases and preceding periods of heavy rainfall [48, 49].

Metals and minerals

Various substances pass a sewage treatment unaffected. They end up in the effluent or in the sewage sludge. If these substances are chemically inert, they will hardly create a direct pollution issue. However, if these substances end up in living creatures or in the food chain, they might cause a threat. Various metals, that are present in food as trace elements, or are even taken in as food supplement for health reasons, are not affected by the aeration of sewage treatment. Metals mainly end up in sewage sludge. Although concentrations in sewage sludge might be small, the use of sludge as fertiliser on farmland might lead to the accumulation of these metals in (top) soil layers. Especially heavy metals like lead (Pb), cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), copper

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[†] The model was created by several national European meteorological institutes, a description can be found at: http://en.vedur.is/weather/articles/nr/3232

(Cu), and iron (Fe) pose problems. Elevated concentrations of metals in soil might lead to diminished plant growth and higher concentrations of these metals in the food chain [53]. Although the human body generally protects itself against the accumulation of too high amounts of heavy metals, heavy metal poisoning might occur and might have serious health effects [54]. For this reason, the EU has set maximum concentrations for Cu and Zn in fertilizer [55]. At the other hand, several heavy metals, like Cu and Zn, are crucial in the food chain: a Zn deficiency might cause loss of appetite, an impaired immune function, and decreased sexual activity. A shortage of Cu might lead to osteoporosis and anaemia. Therefore, there are recommendations for minimum and maximum levels of daily intake. In Europe the main standards for metals in food are the recommendations of the Nordic Council of Minister [56]. Sewage sludge often contains more than 75 ppm Cu and/or 300 ppm Zn, the maximum levels that European regulation allows for agricultural use of sewage sludge [57]. Recovery of these metals is not attractive from the point of view of the value of recovered materials. For example, the largest WWTP of the Netherlands, Harnaschpolder near The Hague, produces annually 49,120 tonnes of sludge, with a dry matter content of 22,8% [58]. Probably this dry matter contains about the maximum concentrations of Cu and Zn that are allowed to be used in agriculture (75 ppm and 300 ppm). In that case, the total amounts are 839 kg Cu and 3,356 kg Zn per year. Naturally these amounts cannot be fully recovered, and certainly not as pure metals, which implies that the total value of the recovered metals will be negligible[‡].

But metal recovery might be of use: lowering the concentrations of metals in sludge might open the way for re-using sewage sludge as fertiliser in agriculture, a circular food chain would be an important step to sustainable development, but would also imply only replenishing mineral losses to the food chain, instead of adding mined minerals to boost agricultural production (e.g., Cu and Zn are added to boost growth of pigs and chicken [59, 60], a.o. phosphates are crucial for plant growth, i.e., crucial for the world wide food production [61]).

There are also precious metals in sewage. Recently this caused interest in sewage sludge after scientists discovered that the sewage sludge of a 1 million inhabitant US city annually contained 13 million USD worth of precious metals [62]. This raised attention throughout the world and various organisations started projects that were aimed at recovering these materials. A sewage treatment facility in Japan, located in an area with many metal, electroplating, and electronics manufacturing industries recovered 1.8 kg of gold per ton of fly ash (the residue of sewage sludge incineration). Sewage sludge with such high gold contents is rare [63, 64].

Phosphates

The removal of phosphates from sewage is important for several reasons:

- Phosphates are a main factor in eutrophication (oversupply of nutrients) of fresh water. Eutrophication causes an overgrowth of algae which remove oxygen from surface water, thereby suffocating marine wildlife [65];
- The stocks of high grade phosphates, mainly in the USA, Morocco and China, are declining. There has been debate on ‘peak phosphates’. However, phosphates are among the first minerals that the world will run out of [66, 67];
- However, most importantly, for the productivity of agriculture, running out of phosphates will be a disaster, as there simply is no alternative to produce the amounts of food that the world needs [68, 69];
- Phosphates might harm the equipment of wastewater treatment plants by spontaneous formation of struvite [70, 71].

[‡] Price indication (March 2017) Cu is about 4 EUR/kg and Zn 1.50 EUR/kg

Phosphates can be recovered in various ways [for history emissions and removal of Phosphates in WWTP's in The Netherlands (Figure 1 and Figure 2)]:

- The preferred way might be to remove it at source: as phosphates are mainly concentrated in urine, separated urine collection might be of interest. Urine might be used directly (in diluted form) as agricultural fertilizer [72];
- The phosphates might be recovered from sewage by adding magnesium to create Struvite. Struvite can be used directly as fertilizer [73];
- Phosphates might also be removed by adding iron-sulphate to the effluent. Iron phosphates are formed which are insoluble;
- Biological removal: phosphate accumulating organisms collect and emit phosphates under specific conditions. By a good process design this principle can be utilized for controlled phosphate removal. In such a case, phosphates end up in the sewage sludge [74].

Sewage sludge is dehydrated and often incinerated. Phosphates can be recovered from the ashes, except when iron is used. In Northern France, Ecophos is constructing a plant for producing fertilizer based on sewage sludge ashes [75].

In general, the early removal of phosphates is to be preferred, as there are fewer damages to the equipment, due to spontaneous Struvite formation. Moreover, if phosphates are removed, the water content of the sewage sludge is less, which implies less sludge to be transported and a more energy efficient incineration of the sludge.

Recovery of phosphates from sewage sludge might also require legal changes, as sewage sludge is determined to be 'waste', there are various legal limits on the use of 'waste' which should be lifted for a circular use of phosphates [76].

Nitrogen

Nitrogen, especially in compounds such as ammonia and nitrogen-oxides, is the other element that is responsible for eutrophication. Nitrogen compounds cannot be washed out chemically. Biological treatment in an anaerobic process might be applied to convert nitrogen compounds into pure nitrogen, which is an inert gas. Traditionally this was carried out by a two-stage process of aerobic nitrification (converting ammonia into nitrates and anaerobic denitrification (converting the nitrates into pure nitrogen. The Anaerobic Ammonium Oxidation (Anammox) process has been developed in the past two decades and removes nitrogen compounds in a single step. In 2007 it was first applied in Rotterdam [77] [for history emissions and removal of Nitrogen in WWTP's in The Netherlands (Figure 1 and Figure 2)].

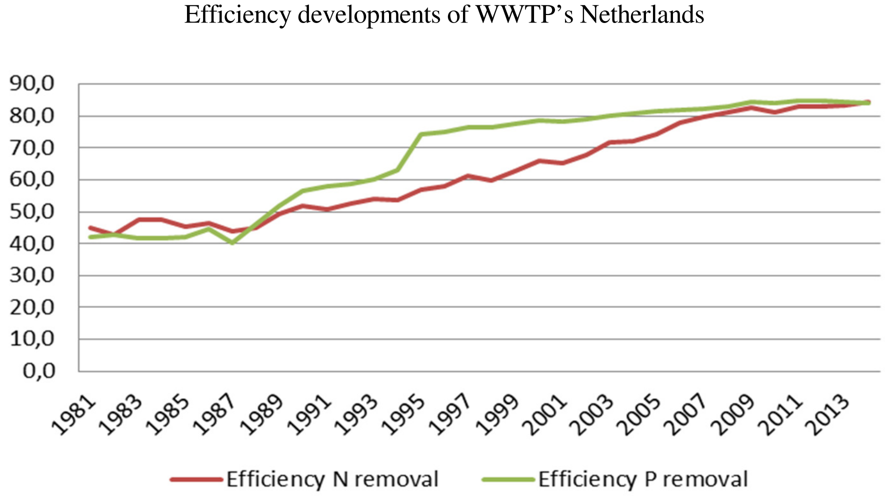

Figure 1. Efficiency development of WWTP's in the Netherlands [78]

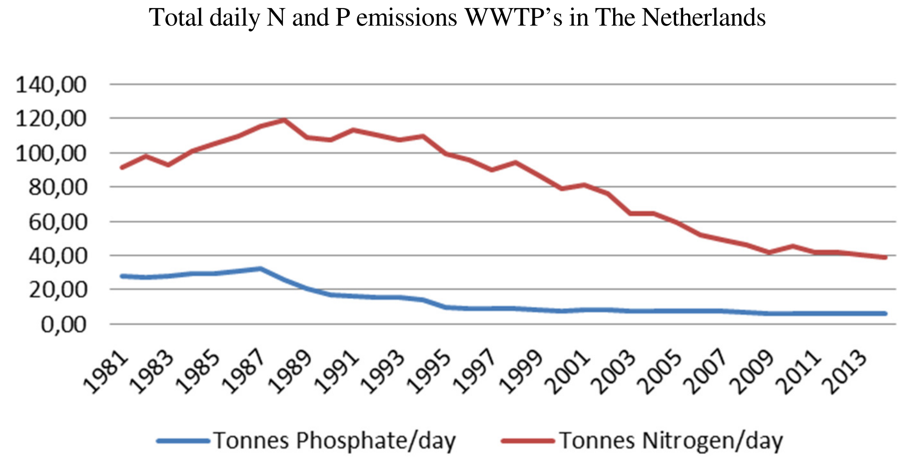

Figure 2. Total daily N and P emissions WWTP's in The Netherlands [78]

Fresh water

The effluent of WWTP's is fresh water with an 'acceptable' level of contaminants. Especially in areas where fresh water is scarce, the effluent can be used as a resource to produce: drinking water, industrial water and irrigation water.

Effluents might also be used to replenish aquifers or to counter the intrusion of saline water. In fact, many WWTP's discharge their effluents at rivers that are used downstream as intake for drinking water [79]. Naturally this poses a risk for drinking water contamination. Several cases of cryptosporidiosis parasite contamination of drinking water, causing infectious diarrhoea, have been reported, e.g. in November 2010, in Ostersund, Sweden [80].

Proteins

The waste water treatment process produces clean effluent and sewage sludge as the residual product of the treatment. Sewage sludge consists for a large part of the remains of bacteria that digested the organic materials that were present in waste water. These bacteria have multiplied during the process, and only a small fraction is recycled internally, to act as the starting population for new generations of bacteria. The bacteria in sewage sludge contain proteins, a resource that might be extracted, e.g. for animal nutrition [81][§].

Cellulose

Toilet paper often ends up as fibrous particles in the WWTP. By using fine-mesh sieves, the cellulose fibres can be successfully removed [82]. This has two advantages:

- The cellulose material that is recovered can be used to dewater the WWTP sewage sludge, it can be used in asphalt [83], and it can be used as raw material for insulation material;
- The cellulose that is removed requires no treatment capacity of the WWTP. Hence, the WWTP might treat more sewage.

Further introduction of sieves to remove cellulose and developing successful cellulose applications is a main challenge for WWTP's. Waste regulations and consumer perception create significant barriers [84].

[§] FoxNews published a story (republished by others) on a burger that was made of these proteins. The story was probably a hoax: https://www.cnet.com/news/japanese-scientist-creates-poop-burger-surely-not/), but is still online: http://www.foxnews.com/tech/2011/06/17/japanese-scientists-create-meat-from-poop.html, [Accessed: 02-May-2018)

Carbon

Organic matter is a valuable resource for agriculture. Productive soil needs carbon, just as it needs various minerals. Crop land loses annually on average 2% of its carbon by decomposition, and it loses some minerals that are washed out by precipitation or taken up by the crop. For this reason, fertilising fields with sewage sludge is a good idea to recycle minerals and carbon. In fact, for millennia, human excrements were used to fertilise the land [85]. However, sewage might contain various harmful substances, such as various toxic chemicals and bacteria. Especially the use of sewage sludge on pasture might affect grazing animals and their products [86].

Another issue might be the accumulation of minerals in the soil. The addition of minerals to the food/water cycle, e.g. by adding minerals as fertilizer, and by adding minerals to animal feedstock creates higher concentrations of minerals in sewage sludge, which might accumulate in soils if sewage sludge is used as fertilizer. For this reason, in the EU sewage sludge is hardly used anymore as fertilizer. The implication is that soils might develop a carbon deficit if no other measures are taken.

Alginates

The NEREDA® process is a novel innovative waste water treatment process: it is a modified activated sludge process that uses granular sludge. Granular sludge settles much faster than the floc like sludge that is formed in the classic WWTP process. In the granular sludge NEO Alginates are formed. Normally alginates are extracted from Chinese seaweed. In the NEREDA® process, alginates are formed that can be harvested easy and energy efficient. Alginates are used to make extra water absorbent- or water-resistant paper. Alginates are also used for hardening of concrete [87].

Hormones

Various (potentially harmful) substances are only partially destructed by the sewage treatment processes. In general, 100% destruction of any chemical will never occur. Some chemicals pass sewage treatment facilities practically unaltered. This applies to various inorganic compounds such as salts and metals. Also, various organic compounds are only partially destructed, like e.g. various medicines and estrogenic compounds. Estrogenic compounds affect the sexual characteristics and behaviour of marine organisms. In a field study in the Netherlands, it was found that downstream of a WWTP, up to one third of the male breams had also female physical characteristics [88]. As these waters might be used downstream as an intake for drinking water, estrogenic compounds could also affect drinking water [89]. If sewage sludge is used for fertilising pasture, these compounds might also affect the food chain [86].

Micro-plastics

Recently, the effluent of WWTP's was identified as a source of micro plastics, that threaten marine wildlife in the oceans [90]. Thus far, there are not much data regarding the behaviour/removal of micro plastics in WWTP's [91]. Polyester micro fibres and micro particles of polyethylene are the most common plastic ingredients of WWTP effluents [92]. The microfibers originate from synthetics clothing, while polyethylene particles are an ingredient of toothpaste and cosmetics. Industry recently announced steps to diminish plastic micro particles in toothpaste and cosmetics [93].

RISKS AND NUISANCES FOR THE SURROUNDINGS

WWTP's and the sewage system cause risks for their surroundings. Some risks are coming from the sewage system itself, like stench, others are an external threat that can possibly affect the system or the surroundings. What is for example the risk of a cyber-attack?

Stench

A well-known challenge for WWTP's is the risk of stench. Next to the fact that stench is an annoying thing, it might also cause health issues such as dizziness, headaches and a bad nights' sleep [94]. An example of dealing with a WWTP stench problem was the new large scale WWTP Harnaschpolder near The Hague which initially caused stench. The stench had multiple causes, in the first place, the sedimentation tank was closed off with floating covers. Along the edges air and the stench could escape. Another problem that occurred was the production of methane, which messed up the bacteria in the WWTP. And the last known cause of the stench was the large amount of long pipelines, needed for transport of waste water in the WWTP [95, 96].

Chemicals and illegal substances

The introduction of new chemicals/pharmaceuticals, like triclosan disinfectants, nonylphenol anti-oxidants and diclofenac pain killers [97], and illegal drug production might disturb the waste water treatment process and biogas production. These substances might also contaminate open waters. Introduction of new chemicals should therefore be monitored. A large dumping of chemicals might kill the microbial process in a WWTP completely. A WWTP might not be able to treat any sewage for 4 to 6 weeks after its microbes have been eradicated. In general, large dumping of chemicals can be detected, and the offenders might be caught by detecting and tracing back the smell in the sewage system manholes. In such cases, illegal narcotic production facilities might be detected [98]. Narcotics and narcotics residue in sewage might be measured to get an indicator of drug use in cities [99]. In the near future, sensor systems might even enable law enforcement agencies to detect the precursors of improvised bombs in the sewage system, which might allow these agencies to dismantle bomb laboratories [100].

Cyber security and Waste Water Treatment Plants

WWTP's just like pumps and valves in the sewage grid are increasingly connected to the internet. This creates a risk of cyber-attacks and hacks. In 2001, an incident occurred in Australia. A former employee of a software vendor hacked into a Queensland WWTP system, and released more than 1,000 m^3 of raw sewage into local rivers and parks. In 2006, a foreign hacker got into the Harrisburg, (Pennsylvania USA) WWTP in an attempt to distribute malware [101]. Naturally, similar actions might play a role in warfare.

Explosions

There have been some examples of accidents causing explosions in sewage systems. In 1987 a tanker lorry entered the city of Herborn, Germany. The brakes did not work and the lorry hit a building and fell over into an ice cream shop. A few minutes later the truck exploded. Gasoline entered into the sewage system. Manhole covers and 12 houses exploded due to the enormous amount of gasoline damps in the sewage system. Even the nearby river Dill caught fire. 6 people died in this accident (Figure 3) [102].

Figure 3. The catastrophe of Herborn, 7 July 1987 [103]

In Guadalajara Mexico, a similar accident happened April 22th 1992, gasoline entered the sewage system by an accident with new gas pipelines. Due to a spark the entire sewage system exploded. Over a total length of 12 kilometres streets and houses were destroyed. A few hours after the first explosion, a second explosion followed. According to official numbers 206 people died [104]. The explosions both were caused by external fluids entering the sewage system. Nowadays, this remains a serious threat for all sewage systems. Although lorries have better safety systems today, accidents like this might still happen.

Sinkholes

Inspections of the sewers are necessary to prevent them from leaking sewage and water. Leaking sewers can cause unstable undergrounds which can cause subsidence or in extreme situations sink holes. Especially in areas build on limestone, where karst is a threat caused by acid precipitation [105].

Sinkholes might appear suddenly in very prominent places like large roads or in residential areas. Roads or houses might disappear in them, with sometimes a fatal ending. While very rare, there are examples of people disappearing in sinkholes, for example Jeffery Bush, who was swallowed by a sinkhole in Florida in 2013. The Tampa area where he lived is known as Sinkhole alley [106, 107].

THE PROBLEM OF CHANGE: LOCK IN IN SEWAGE SYSTEMS

Change is slow in sewage systems. This is caused by lock-in: a sewage system consists of various elements that will never be replaced all at the same moment. The life expectancy of major elements of the system is more than 60 years. This makes it hard to change the system, as it will cause great loss of assets. Moreover, the operations of the current system are well known, and so innovative alternatives imply a destruction of this know how [108].

Also, the factor of spatial corridors is important. In dense cities the space for new corridors for pipelines is limited. Of course, they already exist for the current system, but any structural change will require different dimensions and new corridors. Sewage pipes have to be almost (horizontally) straight, in order to use natural gravity flow conditions. This implies in practice that in dense areas (e.g. downtown), hardly any new sewage pipe might be constructed.

The slow process of change can be illustrated by a comparison between the Amsterdam and The Hague sewage systems. In the early days of sewage different choices were made in both systems. Amsterdam started with a Liernur system, which is based on the collection of the waste for use as agricultural fertilizer. Hence, Amsterdam tried to keep the waste as concentrated as possible and diverted rain water from its system. After the arrival of the water closet Amsterdam had to give up its Liernur system, but soon introduced WWTP's and continued diverting rainfall from its sewage system.

The Hague chose to dig a 'refreshment' canal in order to flush its waste water to the North Sea. Extra water from a water closet or rainwater was no issue, this only helped to get the waste water into the North Sea. In the 1960's, The Hague introduced mechanical treatment, and only in the 1980's full waste water treatment was introduced. Hence, the necessity to separate sewage from precipitation occurred much later in The Hague. Nowadays, the system of Amsterdam is for about 70% a separated system, The Hague's system only for about 30%. The change of the entire system towards a separated system will probably take another century [109].

Not only the life expectancy of the sewage system is one of the problems for change, also the financial side is a factor holding back new developments in sewage systems. When a system is designed for a certain capacity, there is not much interest in measures to lower the supply of sewage. Experiments with innovations like the 'new sanitation system' will lead to less demand for WWTP capacity [51].

Major innovation: 'New sanitation'

In Sneek, the Netherlands, a project called 'Waterschoon' uses a new way of sanitation and separation of the sewage. In Figure 4 is the process of the Waterschoon project shown. Organic waste is grinded and combined with the toilet waste (black water) and transported in a vacuum. The less polluted domestic waste water (grey water) is collected separately. Rain water is directly discharged to the surface water.

Heat is extracted from the grey water. Afterwards it is treated by reed beds and discharged to local surface water.

The black water is digested anaerobically to produce biogas. This energy is used to warm the households of the project. Also the phosphates are collected as Struvite (as mentioned in the paragraph on Phosphates). The advantages of this system: its (vacuum) toilet only uses 1-2 litres of water, against 7 litres of water in a conventional toilet. Biogas production is doubled [51].

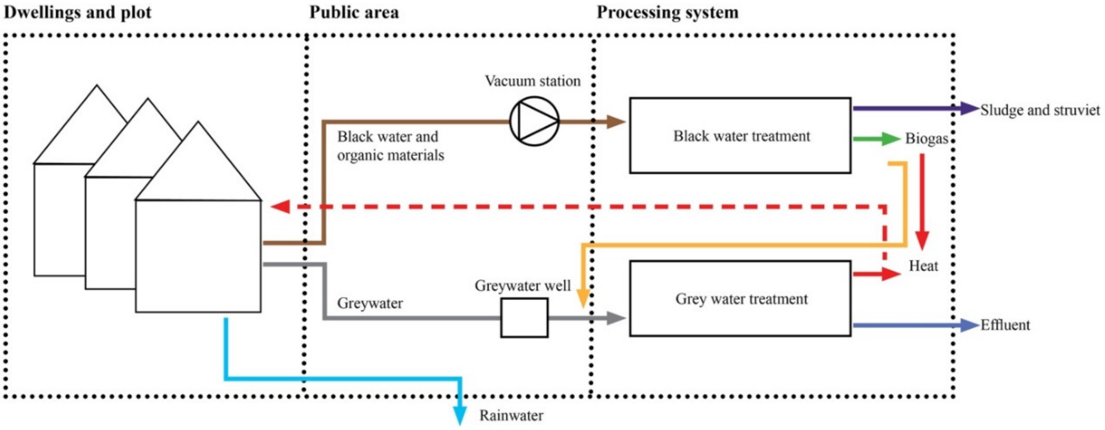

Figure 4. Scheme of project Waterschoon with energy and material flows [110]

Major innovation: NEREDA® process

The NEREDA® process is a modified activated sludge process to produce granular sludge. The sludge settles much faster than the floc like sludge that is formed in the classic WWTP process. This creates large savings as less basins are required and less energy is required [111]. In Epe, the Netherlands the first NEREDA® WWTP is running. The results are claimed to be extremely good [112].

Undoubtedly, the future will bring more innovative options to reduce resource consumption. Especially sensor systems, heat recovery, and recycling and re-use of minerals will be important issues.

CONCLUSION

This paper provides an overview of the challenges that sanitation systems are currently faced with, and briefly sketches barriers to change.

New challenges and new socio-political goals

The sewage and waste water systems as presented are far from perfect, given the challenges of today and the near future. Due to the heavy lock-in and the slow pace of change, the system will not be meeting societal demands soon. But behind the many challenges and options, that are extensively analysed in the literature, and that sometimes exclude each other, there is the question about priorities and goals:

- How important is the scale of the system? Is it an issue of technological/economic optimisation, or should smaller systems be preferred that offer more options for stakeholder involvement and solutions that utilise specific local conditions?

- Should the aquatic environment be restored to pre-human conditions, or should levels of 'acceptable pollution' be set?
- What risk levels are acceptable for what kind of accidents? Are risks acceptable that are new to some places while being well known in other areas (like flooding by extreme rainfall, or longer periods of drought and heat waves)?
- How to recycle resources: At the local level or at continental or global level?
- What will be the role for users of future sewage systems? Do they require a 'flush and forget' system, or can they play a more active and responsible role?

These are socio-political questions that are often neglected. The slow pace of change of sanitary systems creates the opportunity to address these questions, although discussions will probably always be overshadowed by the problems of altering current systems.

The process of change

Implementing solutions for all challenges that were sketched above is hardly possible. Existing systems change very slowly, and new systems are dependent on existing know how, which hardly supports game changing options. Moreover, there will always be new challenges that have not been foreseen, hence, resilient sanitary systems are needed.

Important is that the choices that are made take into account what might be the challenges of tomorrow, as the systems that are created today will probably outlive us by far. As shown before, the historic choices that Amsterdam and The Hague made in the design of their sewage systems about a century ago are still visible and influencing the options of today.

How to accelerate change? The challenges that the external world poses to sanitary systems are enormous. Public support for change is crucial to attract political support for innovation in sanitary systems. To get this support, sanitary systems should be more visible for the public. The public needs to be aware of the challenges, the risks and the options for change [113].

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