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Future Options for Sewage and Drainage Systems Three Scenarios for Transitions and Continuity

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Abstract: The challenge of sustainable development requires cities to aim for drastic improvements in the systems that support its vital functions. Innovating these systems can be extremely hard, and might take lots of time. A transparent and democratic strategy is important to guarantee support for change. Such a process should aim at developing consensus regarding a basic vision to guide the process of systems change. This paper sketches future options for the development of sanitation- and urban drainage systems in industrialized economies. It will provide an analysis of relevant trends for sewage system innovation. In history, sewage systems have emerged from urban sewage and precipitation removal systems, to urban sewage and precipitation removal and cleaning systems. The challenge for the future is recovering energy and resources from sewage systems while maintaining/improving its sanitary service and lowering its emissions.

Keywords: urban sustainability; systems strategy; systems innovation; sewage systems

1. Introduction

The challenge of sustainable development—i.e., bringing the global metabolic processes that provide for human needs within the limitations of our finite planet, and prioritizing the underprivileged in harvesting the fruits of these processes—requires leaps in the resource efficiency of these metabolic processes. Various products and services that we consume daily are provided by large scale socio-technical systems: electricity, drinking water, sewage disposal, waste disposal, transport, heating/cooling. These systems have to improve their resource efficiency drastically or have to be replaced in order to reach the metabolic improvements that are required.

Options for improvement of systems are often limited if one focusses at a single component of a system, as the configuration of the system strongly curbs the options for altering its components. If the basic configuration of a system can be changed, or the system can be replaced by an alternative system, there are far more options for improvement.

However, changing systems, especially the systems in which a lot of investments have been made, can be extremely hard, and might take much time. It might also take a lot of deliberation to reach consensus regarding the most desirable future vision for the system, and the pathways that could lead to that vision. Sustainable development encompasses various challenges, such as climate change mitigation and adaptation, diminishing non-renewable resource consumption, annihilating poverty, and protecting ecosystems and biodiversity. These challenges might lead to counteracting requirements for new systems [1,2].

A change of systems is generally slow. In the process of change, external economic, political, and technological developments might play a role. A transparent and democratic process is important to guarantee support for change. Such a process should aim at developing consensus regarding a basic vision to guide the process of systems change [3–6].

This paper aims at facilitating the process of systems change in sanitation- and drainage systems in industrialized economies, by analyzing the requirements for change and sketching future options for the development of these systems. It will provide an analysis of relevant trends for sewage system innovation. In history, sewage systems have emerged from urban sewage and precipitation removal systems, to urban sewage and precipitation removal and cleaning systems. The challenge for the future is recovering energy and resources from sewage systems while maintaining/improving its sanitary service and lowering its emissions.

2. Methodology

The dynamics of technological systems is determined by the momentum that a system has developed in the course of its development, and its interaction with the external world. Momentum is acquired by the accumulation of capital and knowledge, and the development of an organizational culture. The interaction with the external world creates barriers/threats for a system, that can be elaborated once consensus has been established on critical problems [7,8]. This implies that the history of a system is a major determinant of its future.

In this paper, the history of sewage systems is briefly analyzed in Section 3. The main barriers/threats for sewage systems result from the challenges of sustainable development, in combination with the necessity to fulfil current tasks. These challenges are analyzed in Section 4. In Section 5, options are analyzed that could act as critical problems for further systems development. In Section 6, drivers for change are sketched that determine the future of sewage system and in Section 7, a future outlook is presented for sewage systems.

The material for this study results from a 2.5-year project that involved literature study, interviews, case studies, participation in various symposia and meetings, two student projects, and the feedback of various experts on presentations and papers. I am grateful for the comments and ideas of 4 anonymous reviewers and various colleagues and students: Ben Bonekamp, Tom Goldschmidt, Rob Weerink, Micha Blanken, Cees Verweij, Sabine Eijlander, Johan Krop, Maikel Maloncey, Fred Zoller, and Sita van der Meulen.

3. Background of Sewage Systems

Sewage systems were created to improve the sanitary conditions of cities. Large scale densely populated areas posed a high risk for being wiped out by contagious diseases caused by unsanitary conditions. The Cloaca Maxima constructed about 700 BC [9] is now a rather famous tourist attraction of Rome. However, sewers did not just exist in the capital, they were applied throughout the Roman empire [10,11]. In the Indus Valley, even much older sewers have been excavated [12].

Modern sewage and urban drainage systems started in the 19th century. As compared to the sewers of the Roman Empire, pumping stations were an important new element. Sewers were a solution for a collective problem, public hygiene. In 19th century Europe, such problems had low priority in a political economy that was based on ‘laissez faire’. It took a new large epidemic, cholera, that showed up in Europe in 1831, that made urban sanitary conditions an issue of public concern [13].

Various physicians blamed the stench and vapors of cities as a cause of disease. A breakthrough occurred by the discovery of the geographic correlation between cases of cholera and water consumption from specific drinking water wells. This led to the discovery that cholera was a waterborne disease. Infection was caused by cesspits contaminating drinking water wells [13,14]. Cesspits were temporary underground stores of excrements and waste. The pits were regularly emptied and the content was often used as fertilizer in nearby agriculture [15].

Drinking water contamination and stench were the reasons to create sewers that transported sewage to larger rivers or the sea shore. The London sewers became the exemplars for many cities [16–18].

These sewers also drained the city from excess precipitation, which was beneficial for clearing the sewer pipes. For this reason, sewage systems started as mixed sewage/precipitation systems.

Sewers contributed much to public health, but the rivers that received the sewage were often completely 'dead' and could no longer supply drinking-and irrigation water (Cf. e.g., [19] on problems in the South and East parts of the Netherlands). The only available method to treat the sewage was 'sewage farming'. Sewage farming uses sewage for irrigation of agricultural land. Organics and minerals fertilise the land. However, large areas are required, the method might create chemical and biological risks, and is expensive. Sewage farming often created protest among the affected population [Cf. e.g., [20] on sewage farming near Paris]. As a result, inland cities had problems getting rid of their sewage.

Waste water treatment plants (WWTPs) were developed and introduced between the first and second world wars [21]. The mixed sewage/precipitation sewage systems were not well suited for WWTPs as precipitation diluted the sewage [22] and the irregular supply of sewage, caused by heavy precipitation, could not be processed by WWTPs, and created large sewage spills. However, mixed sewage systems were hard to replace by separated sewage/drainage systems, as the costs of separation were high, and the mixed systems were integrated in the urban fabric. In the 1960s and 70s, sewage treatment intensified and treatment plants became ordinary parts of the urban landscape (See Figure 1). Coastal cities were the last to switch to sewage treatment as they had a cheap way of releasing untreated sewage.

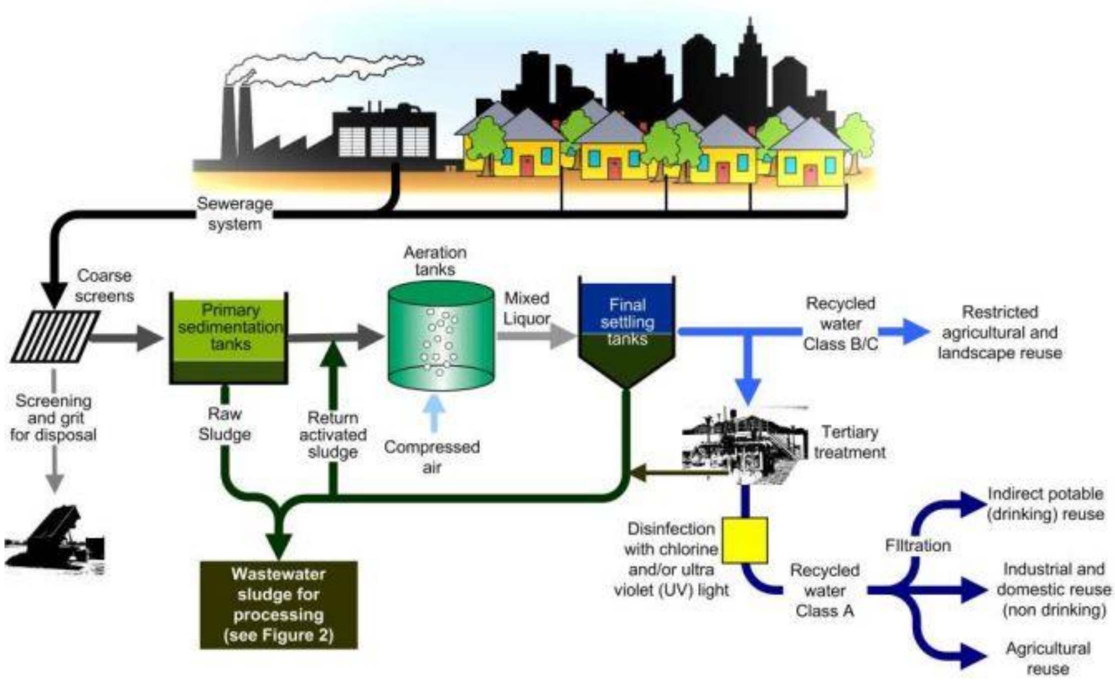

Figure 1. Scheme of traditional sewage system (http://butane.chem.uiuc.edu/pshapley/Environmental/L35/1.html). The sewerage system generally also collects precipitation.

Sewage treatment systems generally used an aerobic (oxygen-rich) biological treatment process. The resulting sludge was initially often used as a fertilizer in agriculture, but this practice diminished by the end of the 20th century due the risk of biological and chemical hazards. In most developed countries, sewage sludge is increasingly incinerated (Cf. [23] for argumentations pro and con incineration of sewage sludge) although there are various options to utilize the resources that are present in sewage sludge more efficiently (see Figure 2).

Over the course of more than one century, sewage- and drainage systems have grown constantly in the area that they serve and in the quality that they deliver. The systems represent a huge capital investment, and a huge investment in expertise and skills. In 2008, the monetary value of the sewage systems (excluding treatment) in the Netherlands (16.4 million inhabitants, 99.5% connected to a sewage system) amounted 62 billion euros [24], which is a clear indication of the financial barriers to creating change.

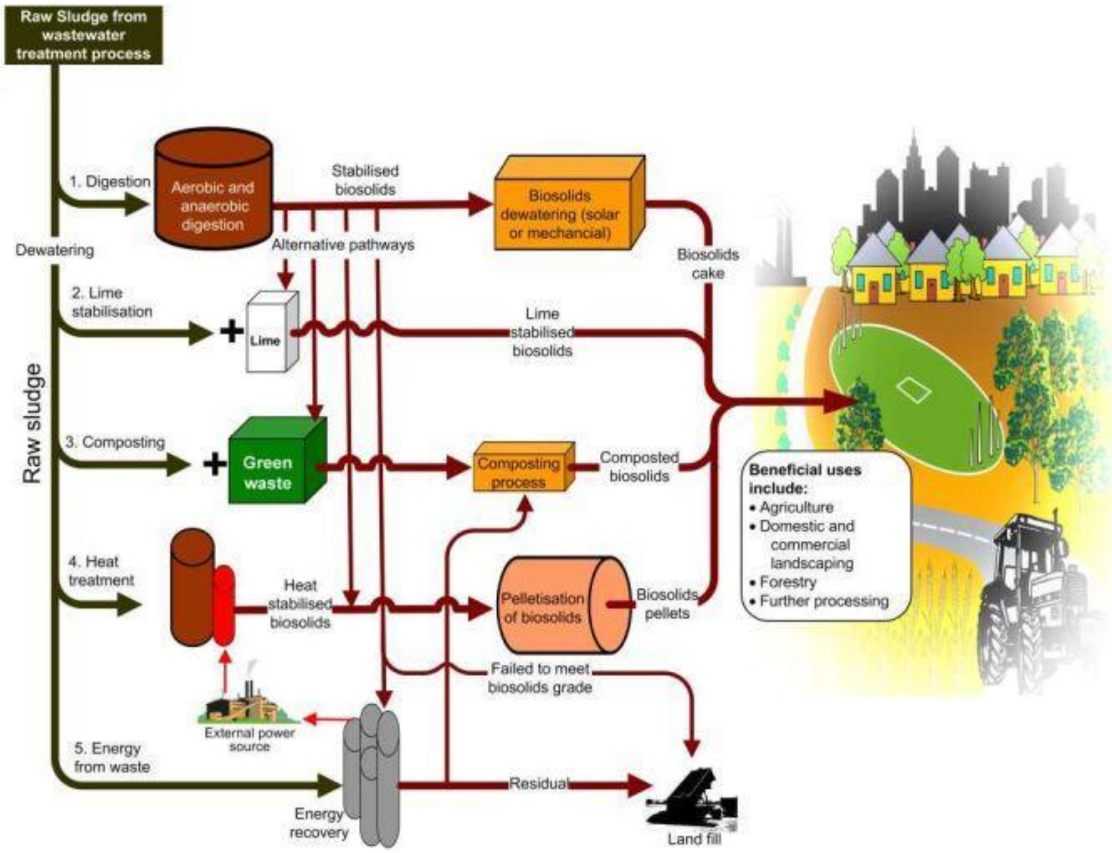

Figure 2. Options for sludge processing (http://butane.chem.uiuc.edu/pshapley/Environmental/L35/1.html).

4. The Challenge of Sustainable Development for Sanitation and Urban Drainage

In the 1990s, sewage systems were often facing the challenge of environmental pollution. New chemicals that were introduced, like phosphates in detergents, created new treatment problems. Heavy rainfall created sewage spills in many cities as the separation of drainage and sewage disposal was generally far from completed. Moreover, the 'stonification' of cities—as citizens increasingly turned their gardens into stone paved terraces, and there were more paved parking's and streets—created higher peaks in drainage, which created more flooding problems.

From the 1990s, the challenge of sustainable development implied that sewage and urban drainage systems should:

- mitigate climate change by reducing greenhouse gas emissions and energy consumption;
- adapt to the impacts of climate change such as increased rainfall and droughts;
- recover resources that are present in sewage;
- contribute to the worldwide conservation of nature and ecosystems by emitting less contaminants.

These goals were added to the existing goals of"

- providing sanitation;
- providing drainage;

- doing so without local environmental harm;
- doing so at acceptable costs.

Causing no local environmental harm has been a goal that is still far from being reached. Especially the inheritance of the past, the 'lock in' of the system in an outdated structure of pipes, that combined sewage and drainage, has prohibited further improvements.

In the remainder of this paper, developments regarding these new goals are sketched. Afterwards, general technological developments that might contribute to solving these new challenges will be discussed, and three options for future sanitation systems are presented:

- improved conventional sanitation
- large-scale anaerobic sanitation
- small-scale/individual sanitation

Probably, the future world will not be technologically homogeneous; different technologies might be used in different local contexts. In the final section we discuss which external trends and local conditions might determine the choice of local sanitation systems.

4.1. Mitigating Climate Change

In order to mitigate climate change, emissions of greenhouse gases should be prevented. In the waste water treatment process, the greenhouse gases CO_2, methane (CH_4) and nitrous oxide (N_2O) are produced [25]. The CO_2 originates from short cycle biomass, and can be neglected here. Short cycle biomass does not contribute to climate change as the CO_2 that the biomass produces is equivalent to the CO_2 that the agricultural production of biomass takes. Nitrous oxide and methane are potent greenhouse gases, which should not be emitted. Methane formation might be stimulated to be used as biofuel that replaces fossil fuels.

In conventional WWTPs, the remaining sludge can be used to produce methane. If an anaerobic (oxygen-free) process is used to treat the sewage, about twice as much methane might be produced [26].

Climate change might also be mitigated by using/recovering the heat that is present in sewage. Sewage temperatures might be as high as 25 °C. Such elevated temperatures are due to improved insulation of dwellings and more hot water consumption at home. Sewage heat might be used for several (larger scale) heating purposes, such as heating swimming pools or office buildings. Generally, heat pumps are required. Naturally, re-using waste heat at home—e.g., by a heat exchanger that pre-heats shower water—is to be preferred to emitting the heat into the sewage system [27].

In WWTPs, sewage needs to be heated before treatment. The effluent is generally still warmer than the ambient temperatures. As this often represents a large quantity of heat, it might be economically used for large scale heating purposes [28].

Sewage might also be used for cooling, although this might lead to accelerated digestion, creating risks of uncontrolled methane formation in sewage pipes [29].

4.2. Adapting to Climate Change

For many European cities, climate change implies that there will be more extreme weather events. More frequent heavy downpours and droughts are most relevant for this paper.

Both for flood risks and for droughts storage of storm water as groundwater might be beneficial. In this way, the groundwater table could be restored, preventing drought damages to trees, buildings, infrastructures and shrubbery, and the risk of flooding could be diminished. Impermeable surfaces should therefore be minimized [30].

Green roofs, wadis, and storage basins are important measures to store precipitation [31]. Flooding is sometimes hardly predictable, and structural measures to prevent flooding might be impossible or too expensive. In such cases, flexible flooding defenses or multifunctional structures might be an option [32].

In mixed sewage/precipitation systems, heavy rainfall generally implies that the WWTP cannot deal with the incoming flow. As a result, untreated waste water has to be released, which creates pollution and health risks. Climate change will aggravate this problem [33]. Decoupling urban drainage from sewage is therefore increasingly important.

4.3. Recovering Resources that Are Present in Sewage

The linear economy will come to an end, as the industrial society cannot continue transforming resources into waste. The cycle has to be closed to prevent creating resource scarcity and high resource costs created by such scarcity. In history, the material flow has been circular from the cesspit and barrel-based collection systems, until the WWTPs of the end of the 20th century: excrements and sewage sludge were used as agricultural fertilizer. However, using sewage sludge brings a risk of biohazards as some pathogens might pass the treatment process. Moreover, there is a risk of chemical contaminants [34]. The introduction of new chemicals and drugs into the consumer market implies that these substances will end up in toilets. Some organic substances and most inorganic ones pass the sewage treatment unaltered.

Sewage contains valuable resources that might be recovered: phosphates, (precious) metals, cellulose, and heat. Some resources might be created in the sewage treatment process such as biogas and alginates [35].

4.4. Contributing to the Conservation of Nature and Ecosystems

The waste water treatment process itself is still far from perfect. Besides emissions of greenhouse gases, WWTPs often cause eutrophication by emissions of organics, phosphates, and nitrates [25].

Another main factor is the continuous introduction of new materials and chemicals in society. For example, oil spills of cars end up in the sewage system, just like (residues of) legal and illegal drugs. Sometimes even small quantities of new chemicals might harm the waste water treatment process, as occurred by the introduction of a new mouthwash [36].

Emissions of heat might be a further element of ecological damage: the heat of effluents might be especially disturbing for ecosystems in inland areas. In winter, such heat emissions might prevent ice covers, while in summer they might endanger aquatic life, especially during heat waves [37].

4.5. Providing Sanitation

Providing sanitation will be an increasingly important task. By shifting climate zones, more persons will be exposed to harmful parasites [38] and pathogens. This might create new local epidemics especially as new health risks might be locally unknown. The quality of sanitation will therefore be increasingly important.

Moreover, more extreme weather, caused by climate change, might create more spills of untreated sewage that might cause additional health risks.

4.6. Providing Drainage

The same applies for the drainage function of the sewage system. Extreme rainfall will occur more often [39]. Precipitation should be kept separated from the wastewater as it will create problems and inefficiencies in the waste water treatment plants. Storage facilities, such as ponds and wadis, might contribute to store peak precipitation (see Section 4.2).

4.7. Local Environmental Harm

Local environmental harm has been the 'raison d'etre' of WWTPs. Besides the impacts mentioned under Section 4.4, stench and incidental spills might be of specific local concern. Stench might be a real nuisance and a health concern for local residents [40]. Depending on the size, local sewage spills might be devastating (see Section 4.4).

A specific form of local harm emerges by the open access of the system: Everybody can flush harmful waste. It is convenient and only by public campaigns, the flushing of most harmful substances can be limited [41]. Chemical waste, especially related to illegal drugs can end up in the sewage system and can ruin WWTPs [42].

4.8. Acceptable Costs

Improving sewage and drainage systems requires additional investments. Such investments are in general covered by municipal or regional taxation. Often these taxes are not depending on income (e.g., taxes per household, per surface area, or per inhabitant), and they cannot be avoided. Extra sewage charges/taxes might create inequity and social problems. Hence, it is important to control costs. Several innovations mentioned in Section 5 could contribute to this aim. New innovative systems will be more expensive, but they are at the beginning of the learning curve, which means that cost savings are to be expected.

Costs of sewage systems should be limited. Costs of abuse of sewage systems (caused by dumping toxic chemicals and solid waste or by damaging the pipes) can be high, and should probably be recovered from the abusers, whenever possible.

5. Main Options for Future Sewage and Drainage Systems

In this paragraph, three clusters of options are sketched for future urban sanitation and drainage systems. The clusters are somewhat stylized and some options could probably also be applied in other clusters, or be combined in hybrid solutions.

5.1. Improving the Traditional System

Sewage and drainage systems emerged as urban ‘removal systems’. Hence, drainage and sewage-removal systems were combined. After large raw sewage releases became unacceptable, the dominant paradigm guiding the design of sewage systems became the ‘flushing and treatment paradigm’ [43].

As a result of history, many sewage systems are still combined sewage/drainage systems. The process of separating drainage and sewage has been extremely slow. As a result, raw sewage is still occasionally emitted into surface water, which creates health risks. Moreover, the efficiency of the sewage treatment process is negatively affected by being fed with variable amounts of precipitation.

5.1.1. Separating Sewage from Drainage

As climate change will cause more instances of extreme precipitation, cities will be forced to improve their drainage, and therefore they might also be able to speed up separating drainage from sanitation. This operation takes huge investments, but as sewage pipes have a long life expectancy, the annual costs are only moderate.

This operation could have another beneficial side effect: The sewage in the pipes of a separated system will have a more constant and higher temperature if precipitation no longer enters the system. Therefore, extracting heat for heating purposes will be more attractive, especially if there is a rather constant heat demand over the year, like for example in the case of a swimming pool. It is estimated that about 15–20% of domestic heat consumption can be recovered from the sewage system [44].

5.1.2. Nereda®, Fast Settling of Sludge

The sewage treatment process might be improved by introducing the NEREDA® (A registered trademark of Royal Haskoning/DHV, https://www.royalhaskoningdhv.com/nereda), technology: Instead of normal activated sludge, this process uses aerobic granular sludge. Such a process has several advantages, the main ones are: The sludge settles much faster, and only a fraction of the basins that are currently used for sludge settling, have to be applied. The cost saving potential is high. Energy consumption is lower and the treatment performance is improved [45,46]. Up to now, the technology has only been developed as a batch process, and therefore process technology is under development to realize continuous treatment [47].

5.1.3. Torrefaction of Sludge

The processing of the WWTP sludge residue might be improved by torrefaction: As sludge still contains considerable amounts of water, transport and incineration is rather energy inefficient. By applying torrefaction—i.e., heat treatment under anaerobic conditions—the sludge residue can be converted into a coal-like fuel that can easily be transported and used for power generation [48].

5.1.4. Minerals Recovery

The ashes that result from the incineration of sewage sludge contain rather high fractions of minerals like for example various (precious) metals [49–51] and phosphates, that might be recovered [52]. In this way, the mineral cycle might be (partly) closed (cf. e.g., [53]). Recovery of precious metals is commercially attractive if there are higher concentrations, caused by e.g., specific industrial activities [49].

More incremental innovations in maintenance of sewers [54], inspection and control systems, wear resistant materials to coat pipes [55], using additives in the WWTP process, handling specific sewage at source (e.g., hospital sewage containing high levels of medicine (cf. [56]) or precipitation from copper and zinc roofs, [57]), might all contribute to a more efficient system.

All these improvements are 'add-ons' as they affect only part of the system, while not affecting its general structure. They are more attractive as the assets of the existing system are hardly affected.

5.2. Anaerobic Sanitation System

Anaerobic sanitation is an option for a radical change in sanitation. It implies changing the whole chain, from toilet, to pipes, to treatment and finally to sludge processing. The core of this change is that anaerobic (i.e., oxygen free) treatment of sewage converts a large fraction of the organic materials into biogas. As the biogas will ultimately also be converted in CO_2, the main advantage is that energy is produced. Such a system can also treat food scrap, which implies that organic waste might be collected by the sewage system. However, the anaerobic treatment system needs a concentrated flow of organic substances. Only little water might be added to the system, and for this reason no water closets can be used. The sewage is transported by vacuum. Waste water with only small fractions of organics should be kept out of the system. Therefore, three flows have to be dealt with separately:

- Excrements and food scrap, to be treated anaerobically.
- Relatively clean and warm water (from shower, laundry). The heat should be recovered and cleaning might be relatively simple, e.g., by reed bed treatment.
- Precipitation should be drained without treatment, or (in case of street pollution) cleaned by a reed bed.

The anaerobic system provides more biogas than conventional sewage systems and might deal with organic waste as well. However, a normal 'flush' sewage system cannot be converted into an anaerobic system, and therefore this system is only appropriate when new urban areas are built, or when a new sewage system is constructed in an existing urban area, preferably in conjunction with new heating solutions. As there are only few anaerobic systems created until now, and the ones that exist are relatively small scale, it is uncertain if an anaerobic system could match the environmental and economic performance of a (improved) traditional sanitation system [26,58]. As many actors in this field are unable to carry the large risks that are involved in applying such an innovative system, a large-scale experiment is urgently needed to establish if anaerobic systems are feasible and viable alternatives to deal with sewage. The city of Amsterdam is preparing for a large scale anaerobic sanitation system, to become operational by 2022 [59].

5.3. Individual Sanitation

Sanitation has long been organized at a micro level: households had cesspits and dung hills as outlets for excrements and household wastes. The content was often used as fertilizer for the fields around cities and villages. It was also used for bringing uncultivated land into culture [60]. In the 20th century, many cesspits were replaced for hygienic reasons. In rural areas, septic tanks replaced the cesspits (septic tanks can provide good sanitation, if the effluent of the tank can be released in a drain field (cf. [53])). In dense areas, sewage systems took over.

Septic tanks have a non-technical advantage: they are generally owned and controlled by the individual that they serve. Proper maintenance can sometimes be a problem, but at the other hand, the owner will take care not to disrupt the treatment process in the tank, for example by poisoning the microbes by flushing harmful chemicals. Harmful chemicals are an increasing problem for regular sewage systems [61]. Many of the synthetic medicines and household chemicals that have been introduced in the market end up in the sewage system [42].

A response to this growing problem of medicines and chemicals might be to return to individual waste water treatment systems, owned by the user. In this way, there will be a strong incentive for the user not to flush any harmful substances. An additional advantage might be that the effluent of such a small-scale treatment (if clean enough) might be locally discharged. In that case, there is no need for separate sewage and drainage systems. Moreover, such micro-scale solutions might contribute to the resilience of the urban society, i.e., diminish vulnerability for catastrophic disruptions. However, there is a risk of negligence, and inspection schemes/sensors might be required.

Could such micro-reactors for digestion of excrements and organic wastes be made at acceptable costs? Micro-reactors have been an important trend in chemical process technology of the past decade. Contrary to conventional large scale reactors of the chemical industry, micro-reactors provide options for better control of process conditions, which might deliver improved products and more safe working conditions [62]. Miniaturization of sensors might support this trend towards micro-reactors [63].

Economies of scale in producing such reactors will be of key importance. The introduction of individual sanitation might be a non-linear process, as for instance economies of scale, leading to lower production costs, leading to rapid market growth, leading to more economies of scale, might play a role. Such mechanisms prohibit reliable future forecasts. At this moment, the options to make a leap in miniature WWTPs are interesting lines of speculation.

6. The Future of Sanitation: Drivers and Barriers for Change

6.1. Sustainable Development Goals

What might be the drivers that could lead to a transition in waste water treatment systems? Main goals for the future of sewage systems might be derived from the UN Sustainable Development Goals. The 17 Sustainable Development goals were adopted by a UN summit 25–27 September 2015 at UN headquarters in New York [64]. While all goals are interrelated, some specifically refer to future sanitation systems as discussed here:

- 2. Zero Hunger
- 3. Good Health and Well Being
- 6. Clean Water and Sanitation
- 7. Affordable and Clean Energy
- 10. Reduced Inequalities
- 11. Sustainable Cities and Communities
- 13. Climate Action
- 14. Life below Water

One can recognize in the SDGs support for the core task of sewage systems: proper sanitation for all (3, 6, 10). Other SDGs can be regarded as new challenges for sewage systems:

- Clean energy and prevention of greenhouse gas emissions connects to 7 and 13
- Prevention of emissions and recovering minerals and materials connects to 2, 11, and 14

As all three clusters of options for the future of sewage systems might contribute to these SDGs, there is demand for innovation as discussed in this paper. However, there are also barriers.

6.2. Forces Prohibiting Radical Innovation in Waste Water Systems

What prevents these innovations from occurring?

6.2.1. Overcapacity

A general factor prohibiting innovation in sewage systems might be the excess treatment capacity of many WWTPs; WWTPs have to serve their own region, as sewage transport is expensive. Due to a gradual decoupling of precipitation from the sewage system, overcapacity in WWTPs developed in many regions. Such overcapacity is a strong argument against innovative sanitation experiments: "No experiments are needed as there is sufficient treatment capacity in the existing WWTPs".

6.2.2. Risk Aversion

Waste water systems, and other urban systems, serve one region or city. If an innovation in a waste water system fails, the costs for the region/city are high. At the other hand, a successful experiment can often easily be copied, as the novelty is not so much based on a specific technological artefact, but on a new way of organizing the system (e.g., all the basic elements of an anaerobic sewage system are around for decades). In general, in a dispersed economic sector, mechanisms to share the risks and benefits of innovation are lacking. This leads to underinvestment in innovation. Such underinvestment can be observed in sanitation systems (cf. e.g., [58]; [65], pp. 205–212, "Why does government intervene?").

6.2.3. Paradigms

Paradigms of expert groups are important in determining which technologies become dominant. History learns that paradigmatic change is a process that takes long time, as it is a process of new young experts replacing the diehards that stick to the established paradigm [66–68].

Hitherto, the civil/sanitation engineers have been quite reluctant in applying technologies other than the traditional flushing system [58].

6.3. Forces Influencing Change

Change is not impossible, and there are ways to promote change that diverges from the established pathways. Whether these novel pathways are to be preferred is still a matter to be decided; however, without further efforts, opportunities might be missed.

6.3.1. Catastrophes

"Never waste a good crisis" is a famous quote attributed to Winston Churchill. It denotes that changes can be introduced if a crisis or catastrophe has had a major public impact like the discovery of the ozone hole [69]. Public health disasters caused by untreated sewage releases or shortages of resources that could be recovered from sewage could perhaps act as such triggers for innovation.

6.3.2. Social Change

The preferences of today, which in part determine market prices, are not fixed forever. New social movements emphasize changing lifestyles, to a more local and a less resource consuming economy. Although life style changes are often received with skepticism, they are a dominant force for long term change.

There are for example growing worries about the whole food cycle. Greenhouse gas and other emissions, animal rights, depletion of phosphate stocks [70,71], deterioration of soils by metals [72], and the effects of warming on eutrophication of water bodies [73] have created public unrest.

There is a growing counter movement: new local products for local communities, small scale agriculture where consumers can check the quality of their own food, micro-breweries, etc. Such development might lead to an emphasis on local circularity in food production and consumption, and smaller scale systems might be important for that. The public unrest might also lead to new measures to restore natural cycles: such measures will definitely affect sewage systems.

6.3.3. External Technological Change

General technological change, e.g., in materials, microbiological processing or control systems, might have a similar impact on various types of sewage systems. Events that are aligned with specific technological options in sewage systems might play a decisive role. For example, nanotechnologies might provide interesting options for health checks by analyzing excrements [74]. Introducing such options could perhaps be combined with the introduction of miniature digesters in toilets. Especially if such health checks are the only feasible way to check for potentially lethal diseases, this might be an attractive combination.

6.4. Promoting Change by Societal Learning

Novel technologies generally are rather inefficient in comparison to the incumbent technologies. The reason is threefold:

- the technology is not optimised by experience in practice;
- users are not used to the specific characteristics of the technology;
- institutional arrangements prohibit an optimal use of the technology.

To create learning in all these domains, it has been proposed to seek, or create niches for novel technologies that could serve as learning environment [75–78]. Such niches could provide the opportunity for a novel technology and its sociotechnical environment to learn and adapt, thereby acquiring the ability to compete with incumbent technologies. Such an approach would probably create less tensions and counteracting measures from incumbents than stringent regulation or strong subsidies [79].

7. Future Outlook

Given the slow pace of technological change in sewage and drainage systems, and the strong (and hardly contested) paradigm in sanitation engineering, it seems most probable that the current sewage and drainage system will not disappear overnight; on the contrary, probably most innovative efforts will be aiming at improving the current system. Options for radical improvement are available but in innovation in general, radical innovations are not pursued as long as there are options for incremental innovation. In the case of typewriters, David clearly showed that the improved performance of a new technology was not sufficient to warrant the considerable investments of switching [80]. As a result, for the foreseeable future, both anaerobic and micro-sanitation will be confined to those specific niches where these technologies have additional advantages.

For anaerobic sanitation the niche might be defined by:

- new urban areas (no existing sanitation system);
- high population density (large volume of sewage per grid investment);
- nearby existing systems cannot accommodate additional users (no WWTP capacity available)
- willingness to contribute to experimentation/scale up of a ‘greener system’ (means for experimentation/willingness to bear somewhat higher risk).

For micro sanitation the opportunities emerge from absence of nearby sewage pipes. Opportunities could emerge for temporary sanitation for festivals, construction sites, etc. These are now served by toilets with excrement storage, but this could produce stench. Another opportunity might be remote dwellings/farms:

- that are not allowed to dispose of sewage by a septic tank (and would need to transport their sewage);
- that are at long distance from the nearest sewage system;
- which could use the biogas produced, and eventually also the remaining sludge;
- that could emit the treated water in nearby waterways (eventually by reed bed filters for further cleaning).

After micro sanitation has been successfully applied in this niche, micro-sanitation might be introduced at those urban spots where it is impossible to introduce a separate sanitation/drainage system: there it will allow turning the mixed drainage/sanitation pipe into a 'clean water' pipe.

For both anaerobic sanitation and micro-sanitation, additional experimentation is required, especially to develop economies of scale, and to handle the remaining biogas and concentrated sludge. Handling the remaining concentrated sludge will also require legal innovations, as the higher concentration of minerals in such sludge implies that the sludge will legally be branded as 'chemical waste'. The paradox here is that increased recycling of a fraction of a waste stream legally transforms the remaining fraction into 'chemical waste'.

The higher concentrations of minerals might facilitate further recycling, or using it as fertilizer, provided that the distribution of fertilizer on crop-land can be well-controlled.

To conclude, progress towards sustainable sewage systems might come from improvement of current sewage systems. The alternatives that might have advantages over the current system will only create marginal threats to conventional sanitation in the short term. In the longer term, a transition might occur, especially if additionally supporting technologies will be available and if developing countries will start 'leapfrogging' to the novel systems. The speed of this transition is not predictable, but might take decades. However, it might be accelerated by future catastrophes, for example climate change might necessitate large investments in sanitation, and this in turn could offer the option to switch to anaerobic sanitation or individual sanitation. The threat of minerals scarcity could also accelerate change.

The transition will take great efforts, not just from technologists but also from economists, politicians, and users. Sewage is a dirty subject that many decision makers do not like to be reminded of, but it is a subject that needs attention in order to contribute to a better world.

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