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APPLICABILITY OF DECENTRALIZED VERSUS CENTRALIZED DRINKING WATER PRODUCTION AND WASTEWATER TREATMENT IN AN OFFICE PARK AS EXAMPLE OF A SUSTAINBLE CIRCULAR ECONOMY IN AMSTERDAM, THE NETHERLANDS*

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Abstract

The Cleantech Playground is a testing ground for innovative clean technologies in Amsterdam, The Netherlands, which aims at closing the cycle as much as possible in a sustainable way. Here, the De Ceuvel is situated. This heavily polluted site features retrofitted houseboats as offices, placed on land, surrounded by soil-cleaning plants. In this Dutch Topsector Water Technology project Waternet, Metabolic, Advanced Waste Water Solutions and KWR Watercycle Research Institute worked together to investigate how local water-related loop closure fits in a sustainable circular economy. Water need has been reduced to a minimum by installing dry composting toilets and the absence of showers and washing machines. Therefore only five liter per capita per day is needed for drinking, food preparation and personal hygiene, compared to the current average of 25 liter in conventional offices and 128 liter in households in The Netherlands. The grey water is treated by biofilters including plants before infiltration. The water supply may pose a potential health risk. In this study, different approaches and technologies for water supply systems have been investigated with respect to hazards to health (with Quantitative Microbial Risk Assessment), sustainability (with Life Cycle Assessment), cost and legal issues. It is a challenge for decentralized systems to achieve the same level of safety as compared to centralized systems without increasing costs and the impact on the environment.

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1. Introduction

The number of (big) cities is growing worldwide, because of urbanization and population growth. Cities consume natural resources, like energy and raw materials, while waste is produced. The generation of waste is growing and an important issue. For more sustainable cities, it is necessary that water, food and energy from the available sources are produced as efficiently as possible. Renewable sources or reuse play an important role and as little as possible value should be destroyed in the system. The water cycle has a crucial role, from clean water production to treatment of wastewater, which contains essential nutrients for agriculture. The current water cycle is linearly arranged from a systemic perspective.

The circular economy is an economic system that is designed to maximize reusability of products and raw materials and to minimize value destruction. In the current linear system raw materials are converted into products to be destroyed after use. Self-sufficient neighborhoods with their own, decentralized water supply add to the image of the circular economy. Currently, in the Dutch water sector, several initiatives can be identified around the recovery and reuse of energy and raw materials (such as phosphate and cellulose).

This study was executed within the Dutch Top Sector Water. Within the various Top Sectors, end-users (often governmental), entrepreneurs and scientists work together in so-called Topconsortia for Knowledge and Innovation (TKI). This TKI project 'Loop-closure Cleantech Playground Amsterdam' is part of TKI Watertechnology and focuses on the water cycle of De Ceuvel in Amsterdam, The Netherlands. The project is a typical TKI Watertechnology collaboration with innovative water technology on the way to market launch in an innovative concept (closure of cycles in practice), with businesses interacting with public organizations and knowledge institutes. This offers advantages for all participating parties.

With this study a practical showcase of local loop-closure in the city is being created and assessed. The primary goal of this small-scale pilot project in Amsterdam, The Netherlands, is to achieve as much as possible cycle closure by applying innovative concepts and technological solutions. The performance, of in particular water-related technology, is monitored in this Dutch TKI project and critically evaluated in order to demonstrate the applicability in a sustainable circular economy.

This study combines innovative high-tech and low-tech installations and makes optimal use of waste materials. It involves the (future) users/residents in the building process and the concept monitoring/evaluation and technology. This is an example of a (future) possible sustainable circular economy. Local energy extraction (heat/electricity) and wastewater/organic waste treatment with nutrient recovery are applied. Research of the feasibility of local drinking water production, including legislation, institutional barriers and regulations, is part of the project. Several possible sources for local drinking water production were investigated; from rainwater and grey water, to local surface water.

Health risks (with Quantitative Microbial Risk Assessment (QMRA)), sustainability aspects (with Life Cycle Assessment (LCA)) and financial consequences have been extensively analyzed. Beside the study of technology performance and development of new solutions for metropolitan areas, human aspects and interactions between users and clean technologies are also studied, to understand how communities can adapt to new systems and changes. In this way, the project provides an ideal case for the circular re-development of metropolitan areas, through R&D activities in a real life environment.

2. Materials and methods

De Ceuvel in Amsterdam, The Netherlands, is a former shipyard that was not used for years. Nowadays completely renovated and insulated houseboats have been installed, which are used as offices for a group of creative initiators, for a 10 year period (Fig. 1). Due to the temporary nature and the highly contaminated soil no new underground infrastructure is constructed. The boats have no gas and no sewage system. Instead, each boat has a heat pump, solar panels, a dry composting toilet and a low-tech biofilter for grey water treatment. Offices are connected to the municipal power grid and drinking water supply, although clean technologies ensure that the use of these common utilities is significantly lower than in conventional offices.

In addition, at the De Ceuvel site a cafe is situated, where urine is collected separately. Centrally located on De Ceuvel is a composting plant, a struvite reactor and a greenhouse where vegetables are grown, potentially with the compost and struvite. The cafe has a conventional centralized sewer connection and water supply. This study focused on the water cycle of De Ceuvel in Amsterdam.

Fig. 1. For a 10 year period completely renovated and insulated houseboats have been installed for use as offices for a group of creative initiators at De Ceuvel in Amsterdam, The Netherlands

LCA was performed to compare sustainability aspects between the centralized and decentralized drinking water production at the De Ceuvel site. For the analyses of the LCA study the SimaPro 8 software has been used, combined with the EcoInvent 3.0 database.

For calculations the ReCiPe Endpoint V1.10 / Europe ReCiPe E/A was applied. If no data specific for The Netherlands were available in the EcoInvent 3.0 database, the following order was applied: RER (rest of Europe), Ch (Switzerland) and then RoW (Rest of the world). The drinking water production at Weesperkarspel (Waternet, Amsterdam) was model for a centralized drinking water production, and De Ceuvel was used as model for the decentralized drinking water production scenario. Data from Barrios et al. (2004) was used for centralized drinking water production. Much information regarding the processes involved in the decentralized scenario came from colleagues at KWR Watercycle Research Institute. Literature was consulted for data regarding usage of UV-lamp and membranes.

QMRA starts by monitoring (or estimating) levels of pathogens in the source water taking into account the variability of contamination due to seasonality or events like CSO (combined sewer overflow) due to heavy rainfall. Then the pathogens removal by drinking water treatment is estimated either by monitoring the indicator organisms removal by the treatment system, or by using process models published in scientific literature. This removal is expressed on a ^{10}log scale, e.g. 2 ^{10}log equals 99% removal. Because viruses are very small they are poorly removed by filtration, and they can survive some disinfection levels. Protozoa like *Cryptosporidium* are larger, but are not affected by chemical disinfection. Because the various pathogens pose different challenges to drinking water treatment, the risk is assessed for four index pathogens: enteroviruses, *Campylobacter* bacteria, *Cryptosporidium* and *Giardia*. For the study of the decentralized systems at De Ceuvel, literature reviews about treatment efficacy were used, since the systems were not built or in operation at the time of the study (Hijnen and Medema, 2010; KWR, 2015; LeChevallier and Au, 2004; Smeets et al., 2006). These reviews made clear that pathogen removal at full scale is generally less effective than at laboratory scale. Upscaling of technology, varying operational conditions and wearing of materials over time lead to less removal in practice than the potential removal reported in scientific literature. For the alternative systems at De Ceuvel both the potential removal (e.g. a newly installed system) and the expected removal (long term performance in practice) are estimated in the risk assessments.

De Ceuvel is actually a very specific situation with 15 offices, resulting in a very low water consumption, because of the installed composting toilets, but also because of the lack of showers. It is interesting to compare centralized and decentralized water systems in a residential neighborhood as well. Therefore the overall costs (i.e. not the consumer price, but the actual production and distribution costs) were compared at two different scales:

1. An office park with 15 offices, inspired from the De Ceuvel real case.
2. A residential neighborhood with 15 family homes.

From the beginning of this project, future users were invited to participate in construction activities at this Do-It-Yourself (DIY) eco-office park. Surveys were conducted during Summer 2014 and December 2014. Results from the survey are shown as indicators of the general opinion of De Ceuvel renters. While during Summer 2014, 8 companies (and users associated) answered the survey, the second survey has been filled by 10 companies. The difference in the number of answers is due to additional companies who settled on De Ceuvel after the summer.

Fig. 2. Grey water treatment in individual low-tech biofilters, consisting of two IBC containers filled with layers of gravel and coarse and fine sand, planted with reeds.

5. Results and discussion

A minimum amount of grey water is produced at the houseboats, since the boats are used as office, they do not have showers or washing machines. Only five liters per capita per day is needed for drinking, food preparation and personal hygiene, compared to the current average of 25 liters in conventional offices and 128 liters in households in The Netherlands (Pieterse-Quirijns *et al.* 2009). The grey water is treated in individual low-tech biofilters, consisting of two IBC containers filled with layers of gravel and coarse and fine sand, planted with reeds (Fig. 2). The effluent of the filters is monitored before it is infiltrated in the soil and complies with the individual wastewater treatment systems norms in The Netherlands (Table 1).

Table 1. Comparison of average monitored influent and effluent quality of grey water biofilters and Dutch standards (Wet Besluit lozen buiten inrichtingen, art. 3.6)

	COD (mg/L	*Total N (mg/L)*	*Total P (mg/L)*	*TSS (mg/L)*
Grey water influent	401	14	1.9	43
Grey water effluent	122	6.8	1.6	37
Standards	200	60	6	60

Composting toilets are being used in the boats. Through the application of composting toilets on De Ceuvel less waste water is produced, but the human feces have to be processed further. The users at De Ceuvel have to bring the fecal matter from their composting toilet periodically to a central composter (type Joraform). Possibilities for reuse of (parts of) compost have been investigated in this study. There is, certainly in the Netherlands, lack of experience in this field. Usually, *E. coli* is used as an indicator of pathogens in a given matrix. However, eggs of worms will survive longer in human feces than *E. coli*. Accordingly, other and/or more than one indicator species should be considered in order to guarantee a reliable safety standard. After 11 months of composting at De Ceuvel, the level of streptococci was reduced by log 1.9. This does not yet meet the WHO recommendation of log 6 reduction by composting.

Pure urine from a waterless urinal at Café De Ceuvel was used for nutrient recovery and tests with pharmaceutical micro-pollutants to investigate contamination of the produced fertilizers and food (tomatoes) grown with these recovered fertilizers (Fig. 3). Micro-pollutant uptake into the fertilizer streams was found to exhibit both high variability and uncertainty for the different pharmaceuticals, which reduced the accuracy by which trends could be identified. However, the concentration of pharmaceuticals in tomatoes was below detection limits (0.02 mg/kg) so the bioaccumulation was calculated at less than 0.03%. These levels were far below the acceptable daily intake (ADI), which is 1% of the minimum therapeutic dose (Hammerton 2016).

It is therefore possible that tomatoes produced using urine-derived struvite-sorbent fertilizers are safe for human consumption. However, although no bio-accumulation was detected in the tomatoes, this does not preclude bio-accumulation in other plant parts, for example the roots or leaves, which were not tested. Because nutrients and other molecules are taken up from soil by the roots, micro-pollutants are more likely to accumulate in root biomass than elsewhere. As humans do not generally consume tomato plant roots and leaves, this is unlikely to directly affect human health. However, this may pose a risk to human health for root crops, such as carrots or radishes, and leafy vegetables, such as lettuces.

Fig. 3. Nutrient recovery and tests with pharmaceutical micro-pollutants to investigate contamination of the produced struvite fertilizers

The goal of the performed LCA study was to compare the environmental impact of centralized and decentralized drinking water production, specific for the operational aspects. For De Ceuvel the following treatment scheme was assumed: 1) raw water intake, 2) ultra-filtration (UF), 3) nano-filtration (NF), 4) UV treatment and 5) remineralization. In this study only consumables for one year performance were taken into account. The goal of both systems is to produce drinking water according to Dutch quality standards. The production of drinking water corresponds to more Ecopoints in the decentralized (0.104) than centralized situation (0.0762), and the difference is approximately 25%. The difference between these two scenarios becomes more significant (60%) when also the distribution network is included in the calculation (Table 2).

The distribution network for the centralized scenario accounts for 37% of the environmental impact, for de decentralized scenario it is 64%. This major difference in impact of the distribution network is a result of the population density, which is relatively high in Amsterdam, while it is low at De Ceuvel. The parameters with the highest impact in the LCA in the centralized scenario were iron for coagulation, electricity for ozonization, sodium hydroxide (NaOH) and electricity for softening. The environmental impact is strongly affected by the energy origin. Improvements in energy demand or (green) energy supply can be implemented both at centralized and decentralized scale and as such there is no difference in environmental impact. The environmental impact was assessed per m^3 of drinking water. The fact that less drinking water is used at De Ceuvel does reduce the environmental impact of operations. The impact of infrastructure, especially distribution, is not affected by the use, since the momentary demand when opening a tap determines the design of this infrastructure.

Table 2. LCA results in Ecopoints for (de-)centralized drinking water production with and without the distribution network in the calculation

	Only drinking water production	***Drinking water production including distribution network***	***Drinking water production including half of the distribution network***
Centralized	0.0762	0.122	0.0991
Decentralized	0.104	0.291	0.198

Currently drinking water at De Ceuvel is supplied through the public centralized drinking water supply system of Waternet. Possibilities to implement local water collection and upgrading towards drinking water quality to achieve a locally closed water cycle were studied. At De Ceuvel, surface water, rainwater and grey water are potential water sources for local drinking water supply (Table 3). These sources are not protected against contamination with pathogens. The proposed treatment system should be capable of producing water that complies with the Dutch drinking water standards with respect to microbial safety with the maximum risk guideline value of 1 infection per 10,000 persons per year. Chemical contaminants may also be relevant for alternative water supply systems (Etchepare and Van der Hoek, 2015), however in this study the focus is on microbial contaminants since they pose an acute health risk. It is possible to produce safe drinking water in a decentralized system (Table 3).

Table 3. QMRA results with surface water, grey water and rain water as water sources for local drinking water supply

		Surface water	***Grey water***	***Rain water***
raw (organisms/L)	*Enterovirus*	0.75	10	0.01
	Campylobacter	453	1.6	24
	Cryptosporidium	3.3	1.2	0.19
	Giardia	3.5	1.2	1.1
total removal (log)	*Enterovirus*	9	5	4
	Campylobacter	10	5	4
	Cryptosporidium	5.5	5	4
	Giardia	5.5	5	4
risk (infections/person*year)	*Enterovirus*	$8.0*10^{-9}$	**$5.0*10^{-3}$**	**$1.2*10^{-4}$**
	Campylobacter	$2.6*10^{-6}$	**$8.8*10^{-4}$**	**$2.7*10^{-1}$**
	Cryptosporidium	$7.1*10^{-5}$	**$2.7*10^{-4}$**	**$9.8*10^{-4}$**
	Giardia	$4.0*10^{-5}$	$2.7*10^{-5}$	**$5.5*10^{-4}$**

The QMRA assumes constant performance of the treatment processes at the proposed level and sufficient operation and maintenance. This requires advanced treatment technologies and strict monitoring and maintenance. The latter will be challenging for consumers with limited knowledge of health risk and about the technologies (Harvey et al. 2015). Replacement of membranes or UV lamps that appear to be still functioning may be considered non-sustainable by end users, thus compromising safety. Monitoring, operation and maintenance would need to be performed by a specialized company, e.g. Waternet. The additional costs and environmental impact of this need to be taken into account when evaluating this option. Monitoring of pathogens in raw water, indicator removal and operational conditions to perform QMRA according to the guidelines would also require substantial resources. Even though the water treatment technology could produce safe water, current monitoring technology is not capable to guarantee continuous safety in an independently operated decentralized system.

Decentralized drinking water production is in theory allowed in The Netherlands when the following three priorities are fulfilled:

1. The drinking water needs a guaranty that it is safe for human consumption.
2. It needs to be produced in a sustainable manner.
3. It needs to be produced against acceptable costs.

However, to ensure that the drinking water quality is guaranteed, a comprehensive monitoring program is needed, which will increase the costs, so it becomes difficult to still produce at acceptable costs. Current quality monitoring regulations appear to make decentralized drinking water production 3 to 10 fold more expensive compared to centralized drinking water production (Fig. 4). Only when the costs for quality monitoring are reduced with about 90%, decentralized drinking water production might be economically more favorable compared to the current costs for centralized drinking water production.

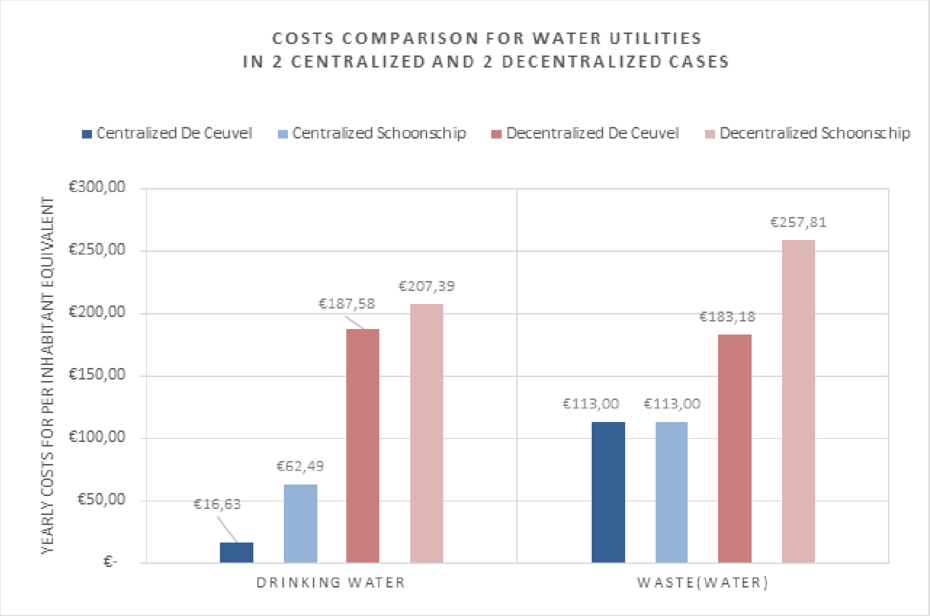

Fig. 4. Cost comparison between centralized and decentralized water facilities for an office park (15 offices 'De Ceuvel') and a residential neighborhood (15 family houses 'Schoonschip')

When labor costs for operation and maintenance are minimized by the deployment of volunteers in decentralized wastewater treatment, overall costs can be comparable with centralized treatment, but such a comparison is not completely fair and certainly not advisable from a risk point of view. Furthermore, in the current costs for centralized drinking water production and wastewater treatment in The Netherlands, several additional costs are included, like costs for environmental protection, research & development and additional taxes.

Finally, user behavior and satisfaction were investigated. It is clear that the occurrence of uncontrolled phenomena such as smells and flies are not acceptable for users. It breaches the comfort level of conventional solutions they are used to. When solutions for each of these issues are implemented, the users are as satisfied with the clean technologies as they are with conventional systems. The first outcome of their feedback is that grey water systems are well accepted among the community, since the removal of settling drums in Fall 2014. Furthermore, regular use of composting toilets is not recommended in the Netherlands, because of discomfort of the users, higher costs and the difficulty to safely reuse the compost. Taken into account the goal of the research at De Ceuvel (local loop-closure) and the lack of a sewer connection, the previous choice for composting toilets is understandable.

6. Concluding remarks

The low-tech biofilters installed on De Ceuvel site (grey water purification systems) ensure sufficient water effluent quality for it to be discharged into the ground without threatening the environment, based on Dutch regulation. Concerning toilet waste composting, results on biological indicators show that toilet waste needs to be composted for a longer period of time in order to ensure safe handling and reuse as a soil conditioner.

The long-term effects of using contaminated urine-derived struvite-sorbent fertilizers on soil quality should also be investigated. It may be necessary to carry out further research in order to determine the indirect risk of using contaminated plant biomass as a feedstock for other purposes, such as compost or animal feed. Further investigation should also be carried out into struvite-sorbent fertilizers for root crops, such as carrots or radishes, and leafy vegetables, such as lettuces. Besides a much larger crop trial, also a broader range of pharmaceuticals are necessary to test the robustness of the preliminary performed experiments.

In addition, feedback from users on De Ceuvel allows for a better understanding of which aspects of the clean technologies are problematic or satisfying. Composting toilets are not well accepted for most of the users. Technical improvements, user-friendly handling and better communication (e.g. operation guidelines) could improve the acceptance, but it is strongly recommended to use other sanitation solutions. Technically local loop-closure is feasible, but user acceptance and especially legislation issues might limit further application. The experiences on De Ceuvel already showed that it is not easy to apply local loop-closure in The Netherlands, but more research and experience with bigger, more representative projects, is needed.

Overall, aspects that could be beneficially applied or prevented in any future decentralized concept can be identified from this study. Decentralised drinking water treatment systems generally have a higher energy requirement per cubic meter of water produced due to the small scale. By reducing the amount of water used, the total use of energy and thus environmental impact will be reduced. When sufficient, sustainable energy is available the total environmental impact and total cost can remain low. For large scale systems, reduced water use has limited effect since its costs and environmental impact depend more on the fixed assets. In comparison with centralized drinking water production, the local drinking water production results in higher risks and costs. Therefore, decentralized drinking water production is not recommended.

Composting toilets are not well accepted by users, because of discomfort and the composting of faecal matter requires a long period of time, since after 11 months of composting *streptococci* reduction did not meet WHO recommendations. Application of composting toilets is therefore not recommended in urban areas. Nevertheless, separated collection of wastewater streams and treatment has potential and could support a circular economy, e.g. nutrient recovery & reuse. Low-tech treatment of limited amounts of grey water with biofiltration is possible. Legal and institutional aspects regarding local water treatment and loop-closure are under development and currently not always clear. Important issues regarding responsibilities, user-acceptance, health and safety risks, sustainability and cost reduction should be further clarified.

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