Decentral drinking water and wastewater treatment at 'De Ceuvel' in Amsterdam

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Abstract
De Ceuvel is a sustainable workplace for creative and social enterprises in Amsterdam, the Netherlands. This heavily polluted former shipyard features 16 retrofitted houseboats, placed on land, surrounded by soil-cleaning plants. At De Ceuvel, small-scale pilot research is performed in order to achieve as far as possible local loop closure. Water need has been reduced to a minimum by installation of dry composting toilets and the absence of showers and washing machines. Therefore, only five litres per capita per day is needed for drinking, food preparation and personal hygiene, compared to the current average of 25 litres in conventional offices and 128 litres in households in The Netherlands. The grey water is successfully treated by individual low-tech biofilters before infiltration. Local production of drinking water is evaluated by Life Cycle Assessment (LCA) and a Quantitative Microbial Risk Assessment (QMRA). The LCA showed that local drinking water production has a lower environmental impact than the current centralised production, but only if a renewable energy source is used and the distribution network was neglected. The conclusion of the QRMA was that locally produced drinking water can meet safety standards when produced from surface water and when sufficient monitoring and maintenance is applied. If grey water is the source, the calculated risks are too high (up to 5 infections per 1,000 persons). Also the safety of the produced compost from human excreta could not be guaranteed; after 11 months of composting *streptococci* reduction did still not meet WHO recommendations. A financial analysis showed that local wastewater treatment as well as local drinking water production was more expensive than the conventional situation. Summarized, local loop closure was difficult to reach at such a small scale, although the chosen techniques were logical at De Ceuvel, due to the lack of a sewer connection.

Keywords
Decentral vs. central; grey water; wastewater; drinking water; LCA; QMRA

INTRODUCTION

Cities are large-scale consumers of resources and producers of waste. Therefore, within cities attention for renewable resources and reuse of waste is important. This paper presents an example of an urban development where this is attempted to the maximum: De Ceuvel. De Ceuvel is a workplace for creative and social enterprises in Amsterdam, The Netherlands. It is located on a heavily polluted former shipyard and features 16 upcycled and retrofitted houseboats, placed on land, surrounded by soil-cleaning plants (Figure 1). Because of the temporary character of the site (rented for 10 years) and the polluted soil, no underground infrastructure has been constructed. The boats have no gas or sewer connection. Instead, each boat has a heat pump, solar panels, a composting toilet and an individual biofilter for grey water treatment. They 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. The (technological) functioning of grey water biofilters and composting toilets was investigated. In addition, desk research was performed to study the feasibility of local drinking water production from a sustainability, health risk and financial point of view. The primary goal of this small-scale pilot project in Amsterdam is to achieve as far as possible closure of the cycle by applying innovative concepts and technological solutions.

Figure 1. Arial view of De Ceuvel.

METHODS AND RESULTS

Grey water treatment

Water need in the former houseboats at De Ceuvel has been reduced to a minimum by installation of dry composting toilets and by the absence of showers and washing machines. Therefore only five litres per capita per day are needed for drinking, food preparation and personal hygiene, compared to the current average of 25 litres in conventional offices and 128 litres in households in The Netherlands (Pieterse-Quirijns et al. 2009). The grey water is treated in individual low-tech biofilters, consisting of two pallet tanks filled with a mixture of gravel and sand, topped with reed (Figure 2). Initially, the system started with settling drums (four 60 litre drums) placed under the kitchen sink in each boat (Figure 3). However, these drums became anaerobic, which resulted in gas production, giving unpleasant smells and complaints by the renters. Therefore, it was decided to remove the drums and completely rely on the biofilters.

Figure 2. Individual biofilter (2 tanks) for grey water treatment.

Figure 3. Settling drums (60 litres per drum) under the sink of a boat.

Water quality parameters of the incoming and outgoing water were monitored, in order to determine the purification performance. The average effluent concentrations (after biofilter passage) compared to the guidelines of individual wastewater treatment systems in The Netherlands are shown in Table 1. From this comparison it can be concluded that the individual biofilters at De Ceuvel produce effluent that is clean enough for soil infiltration.

Table 1. Comparison of average grey water effluent quality from biofilters with Dutch legislation (“Wet Besluit lozen buiten inrichtingen”, art. 3.6)

	COD (mg/L)	Total N (mg/L)	Total P (mg/L)	TSS (mg/L)
Grey water effluent	124	6.9	5.4	35
Guideline	200	60	6	60

Abbreviations: COD = chemical oxygen demand; N = nitrogen; P = phosphorus; TSS = total suspended solids

Composting toilets

Composting toilets use no or little flushing water and are therefore suited to apply in regions with water scarcity. Moreover, due to the limited amount of water, no sewer is needed for wastewater transport. An additional advantage is that nutrients from the excreta can theoretically be reused as fertilizer (Anand and Apul, 2013). Anand and Apul (2010) showed that composting toilets perform better than conventional toilets in a financial and environmental analysis. The main reason to apply composting toilets at De Ceuvel was the lack of a sewer connection. The possibility to reuse the obtained compost as fertilizer was investigated from a safety point of view.

Composting toilets from SunMar are being used in the boats. The users periodically have to bring the faecal matter from the composting toilet to a central composter (type Joraform). The reduction of the level of *streptococci* was measured within this composter. After 11 months of composting, the level was only reduced by log 1.9. This does not yet meet the WHO recommendation of a log 6 reduction by composting. The main reason for the low reduction is probably that the required high temperature (> 50°C) for the composting process was not reached due to the low ambient temperature in The Netherlands.

The experiences of the users with the composting toilets were investigated by a questionnaire. The outcome was that the composting toilets are not well accepted by most of the users: transfer of the compost from the toilets to the central composter and cleaning the toilet is uncomfortable, as it requires handling of human waste. The toilet itself showed design weaknesses (mechanical parts breaking) and clearness of operation guidelines can be optimized.

Life Cycle Assessment

With Life Cycle Assessment (LCA) a comparison was made between the environmental impact of producing 1 m^3 safe potable water centrally or locally. The LCA was performed with SimaPro software, using the EcoInvent 3.0 database and the ReCiPe Endpoint method. The main goal of the LCA study was to obtain insight in the sustainability issues of producing drinking water in a central and decentral scenario. For the central scenario the actual drinking water production for the city of Amsterdam was considered while De Ceuvel was the model for the decentral scenario. For De Ceuvel the following treatment scheme was designed: 1) raw water intake, 2) ultra-filtration (UF), 3) nano-filtration (NF), 4) UV treatment and 5) remineralisation. In this study only consumables for one year performance are taken into account.

The production of drinking water corresponded to more ecopoints/m^3 in the decentral (0.104) than central situation (0.0762) (Figure 4). In this analysis 1,000 ecopoints correspond to the environmental impact of one Western European person per year.

A sensitivity analysis demonstrated that the impact of the distribution network results in an increased environmental impact, especially in the decentralised concept. This is due to the very low drinking water use in the decentral situation. The origin of the electricity also has a strong impact on the environmental impact. In the original LCA, current available Dutch electricity is used, but when a more sustainable electricity source is chosen, the decentral scenario would perform with a lower environmental impact than the central potable water production (if the distribution network is not taken into account).

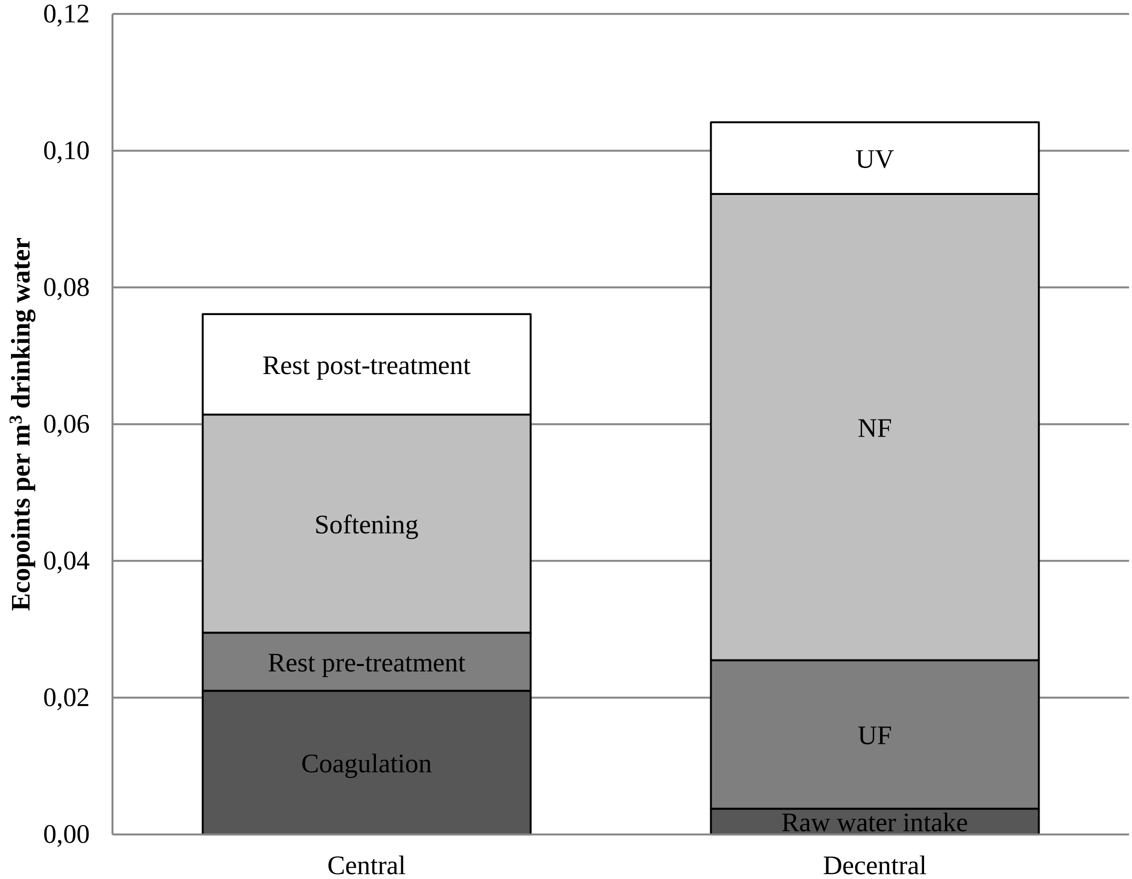

Figure 4. Result of the LCA (without distribution network, with current available Dutch electricity).

Quantitative Microbial Risk Assessment

Water companies in the Netherlands perform quantitative microbial risk assessment (QMRA) to verify that the risk of infection is below 1 per 10,000 persons per year, which is the legal requirement (Bichai and Smeets, 2013). QRMA studies were performed for two cases of decentral drinking water production at De Ceuvel: surface water and grey water as drinking water sources. In the surface water case, a communal treatment system for the whole Ceuvel site is assumed while in the grey water case each houseboat has an individual home treatment system. The exact treatment steps are summarized in Table 2. The applied data (concentrations and removal efficiencies) for the calculations were obtained from literature and the method described in VROM (2005) was used. The results of the QRMA calculations for the two cases are shown in Table 3.

Table 2. The treatment steps assumed for the QRMA calculations

Drinking water from surface water (communal system)	Drinking water from grey water (individual home systems)
1. Pre-disinfection with NaOCl	1. RO membrane filtration
2. Multi-media filtration	2. UV desinfection
3. RO membrane filtration	
4. UV disinfection	

Table 3. QRMA results

		surface water	grey water
raw (org/l)	Enterovirus	0.75	10
	Campylobacter	453	1.6
	Cryptosporidium	3.3	1.2
	Giardia	3.5	1.2
total removal (log)	Enterovirus	9	5
	Campylobacter	10	5
	Cryptosporidium	5.5	5
	Giardia	5.5	5
risk (inf/p*y)	Enterovirus	$8.0*10^{-9}$	$\mathbf{5.0*10^{-3}}$
	Campylobacter	$2.6*10^{-6}$	$\mathbf{8.8*10^{-4}}$
	Cryptosporidium	$7.1*10^{-5}$	$\mathbf{2.7*10^{-4}}$
	Giardia	$4.0*10^{-5}$	$2.7*10^{-5}$

From this table, it can be concluded that it is possible to locally produce safe drinking water from surface water (all health risks are below 1 per 10,000). However, the QMRA assumes constant performance of the treatment processes at the proposed level and sufficient operation and maintenance. This requires skilled operators. Harvey et al. (2015) showed that the level of training has the greatest impact on water quality compliance. For De Ceuvel a local community member would most probably be insufficiently skilled to take responsibility for water supply. Monitoring, operation and maintenance would need to be performed by a specialized company. The additional costs and environmental impact need to be taken into account when evaluating this option. Although the water treatment technology could theoretically produce safe water out of surface water, current (online) monitoring technology is not capable to continuously guarantee its safety.

The risks when individual treatment systems are applied with grey water as a source are too high (up to 5 infections per 1,000). The main uncertainty when using grey water as source is the likelihood of a high contamination level when an infected person contaminates a sink. This would very likely cause the infection to spread to people using that drinking water source. Compared to the decentralized surface water system, the grey water reuse systems would be even more decentralized, with treatment systems in each boat. In that case, the aspects of reliable monitoring, operation, maintenance and performing QMRA would become more important.

Costs

A financial comparison between central and decentral water facilities was also made. All costs for water production, distribution, consumption, collection, purification, quality monitoring, management, maintenance and operation were considered, for both wastewater handling and drinking water delivery. Table 4 shows the different situations that are considered for the costs calculation.

Tabel 4. Situations that are used for the costs calculations

	Centralized	**Decentralized**
Drinking water	Municipal supply	Reverse osmosis unit using water from the canal, two scenarios for monitoring
Grey water	Discharged to the sewer, purified in municipal wastewater treatment plant	On-site biofiltration, infiltration into the ground
Toilet waste	Flushed to the sewer, purified in municipal wastewater treatment plant	Collected with dry toilets and composted, two scenarios for labour costs

Monitoring of drinking water quality is expensive in the decentralized case, mainly because it is not possible to downscale the obligatory monitoring program. Total costs of the program are comparable to the central case, but for a far lower amount of produced drinking water. Therefore, a scenario with a 90% reduction of these monitoring costs was also calculated. Since the handling of the compost is done voluntary at De Ceuvel, a scenario is calculated without labour costs for the toilet waste work.

Figure 5 shows the results of the financial comparison. It is concluded that even without labour costs or expensive obligated monitoring, central wastewater treatment and drinking water production are cheaper. An important reason for this is that De Ceuvel is very small (only 16 houseboats with office function). The water use is very low, which makes the costs to deliver or treat it high. The Foundation for Applied Water Research STOWA (2014) calculated that at least 1,200 people equivalents are needed for local treatment of separated collected wastewater to be economically feasible in the Netherlands.

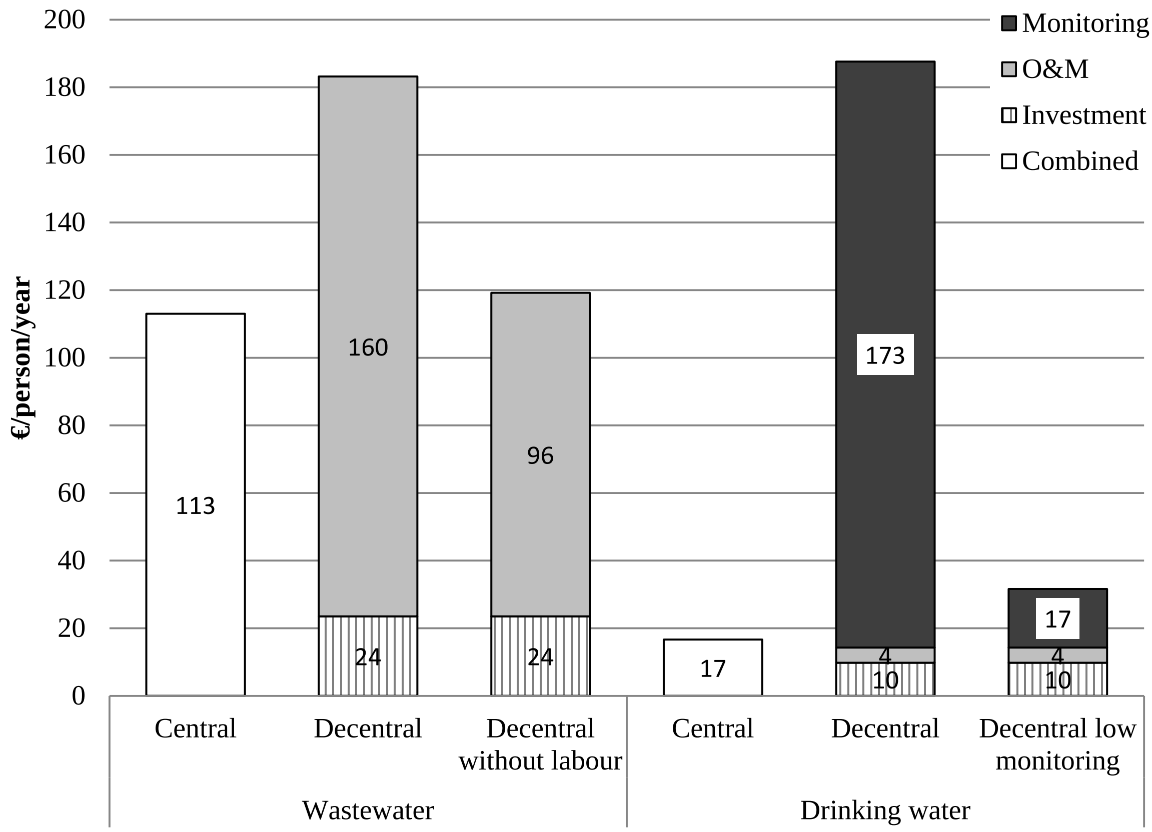

Figure 5. Outcome of the costs calculation

CONCLUSIONS

Research at the small-scale pilot project De Ceuvel in Amsterdam showed that local loop closure of the water cycle is hard to realize. Reduction of water use was achieved by the lack of showers and washing machines in the offices and by using composting toilets instead of flushing toilets. The remaining amount of grey wastewater (5 L per day) was successfully treated in individual biofilters, whose average effluent concentrations complied with the Dutch legislation. However, a QRMA study showed that the potential risks of using this treated grey water as source for drinking water were too high (up to 5 infections per 1,000 persons). When surface water is used as a source, locally produced drinking water can meet safety standards if sufficient monitoring and maintenance is applied. The latter however, is challenging and costly. An LCA study demonstrated that locally produced drinking water has a higher environmental impact than centrally produced drinking water. Locally produced drinking water can be more environmental friendly only if renewable electricity is used and the impact of a distribution network is neglected. Decentral drinking water delivery is more expensive than conventional centrally produced drinking water, which is mainly due to high monitoring costs. Considering these three disadvantages, no further research or developments on local drinking water production in Amsterdam will be planned in the near future.

The main reason to use composting toilets at De Ceuvel was the lack of a sewer connection. The collected human excreta were periodically transferred from the toilets to a central composter on site. Measurements showed that efficient composting of faecal matter requires a long period of time; after 11 months of composting *streptococci* reduction still did not meet WHO recommendations. In addition, the composting toilets were not fully accepted by the users, mainly due to the necessity to handle human waste. The applied decentral wastewater treatment (grey water biofilters and composting toilets) was more expensive than conventional central treatment. The difference was small when the handling of the compost was assumed to be done by volunteers (no labour costs), as is the case at De Ceuvel. It can be concluded that a regular use of composting toilets is not recommended in the Netherlands, because of discomfort of the users, higher costs and impossibility to safely reuse the compost. In a situation without a sewer connection like De Ceuvel, however, it is probably the most sustainable solution. Taken into account the goal of the research at De Ceuvel (local loop closure), the use of composting toilets is understandable.

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