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Rainwater harvesting in the Netherlands: useful or not?

Roberta Hofman-Caris, Cheryl Bertelkamp, Luuk de Waal, Tessa van den Brand, René van der Aa, Jan Peter van der Hoek

Rainwater harvesting, run-off, first flush, sustainability, drinking water, water treatment

Often rainwater harvesting is considered as an important contribution to a more sustainable society. Rainwater is assumed to be clean water, requiring only limited treatment, and it is thought that there is sufficient rainwater available to provide people with drinking water. In order to check these assumptions, we carried out a desk study into the quality and quantity of rainwater. It was found that rainwater is cleaner than surface water, but still may contain contaminants. Especially the microbiological quality of rainwater is a point of concern, and therefore treatment, including disinfection, will be required. Furthermore, it was found that for densely populated areas, like a city district in Amsterdam, the quantity of rainwater that can be harvested from both built and paved surfaces equals only about half the amount that is required for the inhabitants. If rainwater is collected and treated at a neighborhood level, the costs are in the same order of magnitude as for centralized drinking water treatment. However, at the level of a single house costs are significantly higher. As rainwater requires less treatment than e.g. surface water, a small decrease in environmental impact may be realized.

1. Introduction

Some people consider rainwater harvesting as one of the measures that could significantly contribute to a more sustainable society. Rainwater is thought to be clean and many people have the impression that e.g. in the Netherlands there is ample rainwater available. Several drinking water companies are investigating rainwater harvesting as a possible source for drinking water production. In this paper we describe the results of an investigation to find an answer to the questions whether indeed rainwater is a clean source for drinking water and whether there would be enough rainwater to provide people with sufficient drinking water. Furthermore, it was calculated what the total cost of ownership (TCO) would be for drinking water production in a city district and for a single house in a rural area. Besides, a life cycle assessment (LCA) was made for both situations.

2. Methods

There is limited information available on rainwater composition in the Netherlands, but in international literature several studies can be found on the compounds that are determined in rainwater. Furthermore, we evaluated the precipitation data of the KNMI (the Royal Dutch Meteorological Institute) all over the Netherlands in the past ten years and combined them with data on the average use of drinking water.

For the TCO calculation a handbook for the calculation of small treatment processes was used [1]. A LCA was made by applying SimaPro 8 software applying the ReCiPe Endpoint (E) and data from the EcoInvent 3.0 database. Calculations were based only on consumables (like chemicals and energy), as it is very difficult to calculate how much existing equipment, like pumps, reactors and tubing, contribute to the footprint.

In order to calculate the "savings" by decreasing the impact of rainwater, the situation in Berlin was taken as a starting point. Here, taxes are levied to compensate for the costs for water treatment and nuisance caused by (heavy) showers, when the water cannot be drained because of the presence of paved surface etc. These taxes amount to €1,84/m² of paved surface area [2], and a similar amount of money was taken as a measure for the savings due to rainwater harvesting.

3. Results

3.1 Rainwater composition

In the Netherlands about 60% of the drinking water is produced from groundwater, which is a relatively clean source. 40% is based on surface water from the rivers Rhine and Meuse. These contain a broad range of micro-

Table 1: *Presence of inorganic ions in rainwater and their origin*

Ion	Origin
SO_4^{2-}	Industry, traffic, fuel. Part has a marine origin, but also application of fertilizers contributes to the sulfate content
NO_3^-	Industry, traffic, fuel
HCO_3^-	Dust
Cl^-	Mainly marine
PO_4^{3-}	Use of fertilizers
H^+	pH has been decreasing in the past decades [4, 5]
Ca^{2+}	Dust
K^+	Soil, fertilizer, biotic sources, burning of biomass
Na^+	Marine
Mg^{2+}	Marine
NH_4^+	Fertilizers

pollutants. Recently, there has been much attention for the increasing loads of pharmaceuticals in surface water. This is caused by the fact that wastewater treatment plants (WWTPs) in general have not been designed to deal with such compounds, and thus can only remove about 60-70% [3]. The remainder stays present in the effluent and is discharged into surface water. Rainwater doesn't contain any WWTP effluent, and thus also won't contain as many micropollutants. Besides, the hardness of rainwater is very low. However, does this mean that rainwater consists of merely pure water?

Most literature on the composition of rainwater focusses on the presence of inorganic compounds. **Table 1** shows the most common ions that can be found in rainwater and their origin.

It was observed that the cation concentrations often are higher than the anion concentrations, which indicates that the water probably also contains small organic acids. Cindoruk et al. showed that organochlorine pesticides can be found in rainwater in several places in the world [6]. The presence of polycyclic hydrocarbons was demonstrated by Angrill et al. [7] and Göbel et al. [8].

Apart from the ions mentioned in **Table 1**, rainwater can also contain traces of iron, copper, cadmium, manganese, lead, zinc, nitrite, bromate and fluoride [9-12]. Many of these compounds are of anthropogenic origin. According to Iavorivska et al. [13] yearly over the whole world 1108 Tg of carbon is emitted. 305-550 Tg of this amount precipitates on the surface (including 6-46 Tg/year of fossile origin), 60% of it via rain. According to Bhaskar et al. [4], 90% of the total load of pollutants in the atmosphere precipitates by means of rain. Thus, although rainwater contains less micropollutants than surface water, it often will contain some pollutants.

However, problems with water quality mainly arise from the collection of water. Surfaces, like roofs, are often covered with dry and wet precipitation, animal feces, and parts of plants, which end up in collected rain water [14, 15]. Additionally, because of the low water hardness, metals and carbonate from the roof material can be dissolved [8, 12, 16]. As a result, the quality of the water collected from roofs is worse than that of the rainwater itself. Factors that affect the influence of the roof are the type of surface (a rough surface in general contains more contaminants than a smooth surface), the angle and direction of the roof [17]. Especially the microbial contamination of the water is a problem if the water is to be used as drinking water: a robust disinfection is a prerequisite [7, 14, 18, 19]. According to an investigation of Boogaard and Lemmen [20] similar results were obtained for collected Dutch rainwater. The microbial contamination of the water is a point of concern. It won't be worse than the quality of surface water, but for decentralized treatment systems it will be more difficult to safeguard water quality.

In order to improve the quality of collected rainwater, often a so called "first flush" is applied: the first amount of rainwater is disposed of, as this contains the highest concentrations of contaminants [14, 17, 21-25]. How large this first flush should be depends on the situation: the type and location of the roof, but also on the length of the dry period preceding the rain period, as during this period contaminants are collected at the roof. In general, the first 0.11 to 3.8 mm (for horizontal roofs covered with gravel) will have to be disposed of.

3.2 Amounts of rainwater

The KNMI collects rainwater data of about 25 meteorological weather stations and 325 stations for deposition measurements. Data, obtained between 2006 and 2016, of six of these stations, spread across the country, were evaluated. It was found that the total amount of rain increased from 814 mm in 2006 to 856 mm in 2016. This is mainly due to more heavy showers that seem to occur in recent years. For the possible production of drinking water, we applied a first flush of 2 mm. This means that for every event of rainfall the first 2 mm are discarded. This may not always be necessary, and it would be better to adjust the first flush to the actual situation, concerning the amount of pollution on the roof (and thus e.g. the length of the dry period preceding the rainfall). However, in all technical applications in literature a constant first flush is applied, which ensures a higher quality of the harvested water. The second parameter to take into account in calculating the amount of rainwater that can be harvested is the run-off coefficient. How much water can be collected depends on the type and angle of the roof and the amounts that disappear by evaporation or leakage. The run-off coefficient represents the ratio of rainwater that can be harvested to the total amount of rainwater that falls on a roof. On average this factor is about 0.8 [22]. Taking into account both the first flush and the run-off coefficient, the part of the rainwater that can be harvested for the six weather stations studied is shown in **Table 2**. The data are similar for the different areas.

In the Netherlands the average roof has a surface area of 60 m² [26], and an average household consists of 2.2 persons [27]. In **Table 3** an overview is given of the average use of drinking water in relation to the amount of rainwater that can be harvested, with and without applying a first flush. If the water e.g. only would be used for toilet flushing, there is no need for a first flush.

From **Table 3** it can be concluded that without a first flush the amount of rainwater that can be harvested from an average roof equals the amount of water that an average household would require for showers. However, using untreated rainwater for taking a shower cannot be recommended, as the microbial safety of the water certainly isn't guaranteed. With application of a first flush 60% of the water needed for the shower is available. Thus, the amount of rainwater harvested certainly won't cover the drinking water demand of an average household. If the water is going to be used for consumption, certainly thorough purification will be required in order to guarantee especially the microbiological safety of the water. At the moment this still presents a practical problem, as there aren't yet suitable sensors available to monitor the water quality. As a result, regularly expensive analyses will be required in order to check whether the purification still functions adequately.

4. Rainwater as an alternative source for drinking water

There are some ways in which sufficient rainwater can be harvested to produce drinking water. People can use equipment that requires less water, like vacuum toilets and water-saving showers. However, this still will not totally solve the problem of the insufficient amounts of rainwater that can be harvested for all household applications. This problem may be solved if not only water from roofs but also from paved surfaces would be harvested. The water quality may be a little less than the quality of water harvested from roofs, but the difference is relatively small. Rainwater still will not contain compounds originating from WWTP effluent. Drinking water production at neighborhood level should be carried out under supervision of a drinking water utility in order to guarantee safety. If in a relatively small town like Hilversum (The Netherlands), with a population density of about 960 persons/km², all rainwater from paved and built surfaces is collected, this would be sufficient to cover the water demand of the inhabitants. This water demand would be about 420*103 m³/year, whereas the amount that can be harvested would be about 2,000*103 m³/year.

Table 2: *Possibilities for rainwater harvesting spread over the Netherlands, taking into account both the first flush and the run-off coefficient*

Weather station	Percentage of total rainwater that can be harvested (%)
De Bilt	51
De Kooy	48
Maastricht	49
Nieuw Beerta	46
Twente	48
Vlissingen	48
Average	48

Table 3: *Amount of water required for an average household. Without first flush 41 m³/year can be harvested, whereas with application of a first flush 24.8 m³/year can be harvested.*

Application	L per person per day	m³ per household (2.2 p) per year
Shower	51.2	41.1
Bath	2.4	1.9
Sink	4.8	3.9
Toilet flushing	33.3	26.7
Washing of clothes	14.3	11.5
Dish washing (both manual and by dishwasher)	6.0	4.8
Preparation of food	1.9	1.5
Drinking	1.9	1.5
Others	3.4	2.7
Total	**119.2**	**95.7**

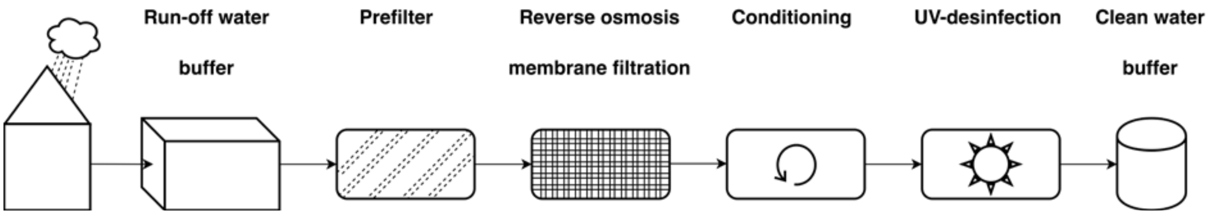

Figure 1: *Schematic overview of a small-scale water treatment process based on RO*

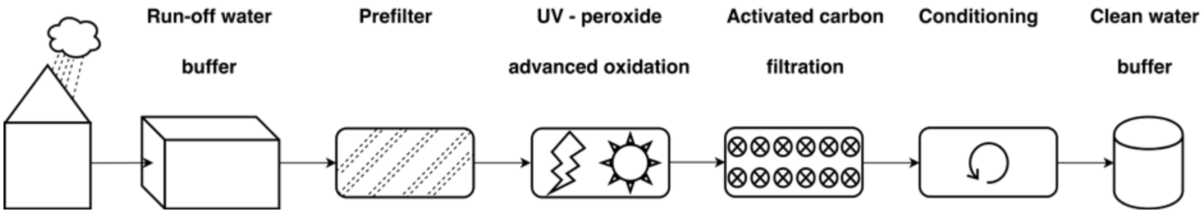

Figure 2: *Schematic overview of a small-scale water treatment process based on AOP*

Waternet, the water utility of the city of Amsterdam and surroundings, wanted to determine the costs and environmental impact if rainwater would be harvested and used to produce drinking water in two cases:

- a new city district that is being developed in Amsterdam
- a single house in the rural area outside Amsterdam

For the city district the calculations were based on the city government plans for layout of the area [28]. The surface area of the new district, which is to be located on an artificial island in the water IJ, is 13,000 m², and it will contain 1300 houses, partly single houses, partly apartment buildings. The total built and paved surface in this district is expected to be 93,600 m². Based on the KNMI data and an average run-off coefficient of 0.8, 685 mm of rainfall could be harvested. Thus, it can be calculated that a maximum of 6.41*103 m³ of water may be harvested in this district. In the Netherlands the average number of people in one household is 2.2, and assuming a daily water use of 120 L per person, the amount of rainwater harvested will cover about 51% of the water demand. Even if water-saving measures would be taken, and e.g. vacuum toilets would be installed, the amount of rainwater harvested wouldn't cover the water demand of the inhabitants of the district.

Combining rainwater harvesting with the regular central water production and distribution might solve this problem but would cause another kind of problems. As water utilities are obliged to deliver enough drinking water at every moment, the capacity of the treatment process and the network would have to be about identical to the regular capacity required in order to be able to provide enough drinking water during periods of drought. However, there would also be periods in which the flow through the network would be lower. The network is designed in order to be "self-cleaning" at a certain flow [29, 30], but in this case the self-cleaning capacity of the network would decrease. And as the residence time increases at lower flow rates, the water quality may be at risk. At the same time, the price for centrally produced drinking water would have to increase, as the same investment and operating costs will have to be paid at a lower production volume. An alternative would be the combination of rainwater harvesting with other sources, like reuse of grey water, but this has not been investigated within the framework of this research.

For both the city district and the single house the TCO were calculated. Two main treatment processes were taken into account:

- reverse osmosis, followed by conditioning (to adjust water hardness and pH), UV disinfection and storage
- rapid sand filtration, followed by advanced oxidation (UV/H_2O_2), filtration over activated carbon (in order to remove the excess of H_2O_2 and byproducts that may have been formed), conditioning, and storage

For the city district, is was suggested to collect the rainwater in an open pond. In order to be able to harvest sufficient water and to prevent nuisance from heavy showers, the volume of this pond will have to be 14,000 m³, or, at a depth of 4 m, it would require an area of about 3,500 m², which equals about half the area of all sports fields and parks planned in the district.

For the single house, a pond of 20 m³ would be required, but it can be doubted whether the presence of such a large pond, which will be nearly empty during most part of the year, in the vicinity of a house would be desirable. Therefore, we also made calculations for a situation in which water is collected in a closed tank. As untreated water cannot be stored for a longer period of time, and as the tank will have to be emptied within a short period of time (in order to be able to collect the next rain shower), the treatment capacity of the process will have to be relatively large in this case, although it will only be in use occasionally. This results in relatively high costs for investments and operation of the system.

A schematic overview of the treatment processes is given in **Figures 1 and 2**.

Table 4: *TCO and environmental impact for rainwater harvesting and decentralized drinking water production*

Case	Total costs (including analyses costs) (€/m³)	Possible savings ("taxes") (€/m³)	Net costs (production + analysis – savings) (€/m³)	Environmental impact (mPt/m³)
City district*	2.70–3.50	1.60	1.10–1.90	13
Single house, closed tank	111.00	4.50	106.50	29
Single house, open pond	64.00	2.70	61.30	29
Present centralized process	1.63**	0		36

* The costs refer to the production costs taking into account a buffer to cover the water demand during a period of six weeks of drought. A back-up network from the centralized treatment system, which may be required, is not taken into account in these calculations. This would increase the total costs of the system.

** This price includes certain taxes, administration etc. [32].

In order to be able to guarantee the safety of the drinking water produced, regular analyses will be required. The average yearly costs for such analyses will be about €2,500 independently of the volume of water produced. As a result, the analyses costs amount €0.04/m³ for the city district, and €25.93/m³ for the single house, where the production volume is significantly smaller. For reason of comparison in this paper, all costs are calculated per m³ of drinking water.
For all these situations the environmental impact was calculated, expressed as ecopoints (Pt). The average footprint of a Western-European person is 1,000 Pt/year [31]. The advantage of using ecopoints is that in this way, contrarily to the CO_2 footprint, the full environmental impact is covered, including land use and exhaustion of raw materials. However, the CO_2 footprint has additionally been calculated for comparison purposes.
The results of these calculations are shown in **Table 4**. They are compared with the present total costs for drinking water in Amsterdam.
From **Table 4** it can be concluded that the costs for rainwater harvesting in the city district may become comparable to the present costs, if savings caused by less nuisance are also included. However, for the single house the costs are very high.

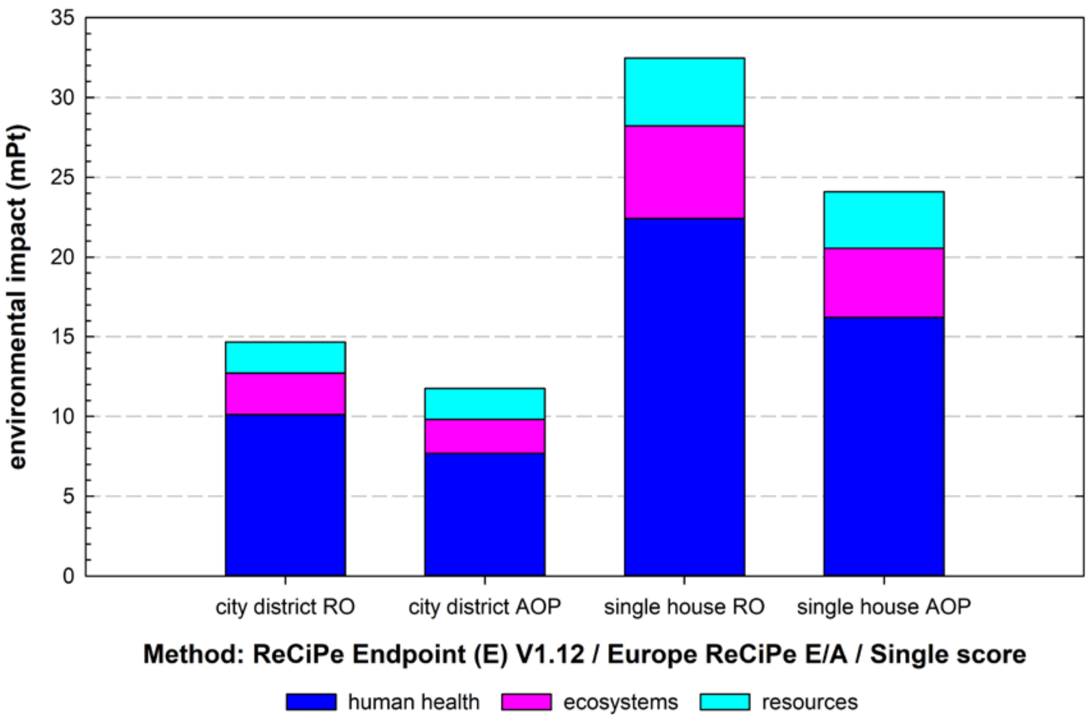

Figure 3: *Single point score of four scenarios in LCA*

Table 5: Footprint in ecopoints and kg CO_2

case	Total impact (mPt)	CO_2 footprint (kg CO_2)
Present process	36	0.130
City district	13	0.004
Single house, closed tank	29	0.003

Indeed, the environmental impact of the water treatment process appears to decrease when rainwater is used instead of surface water as a source for drinking water production. This can be explained from the fact the rainwater contains less anthropogenic contaminants than surface water, and thus requires a less complicated treatment process. A single point analysis is shown in **Figure 3**. For the LCA it doesn't matter whether an open pond or a closed tank is used, as only consumables are taken into account. In general, the AOP process has a smaller impact than the RO process. Furthermore, it can be concluded that the impact of the process for the single house is much larger than the impact of a treatment process for a city district.

Although rainwater harvesting obviously results in a smaller footprint, things will still have to be placed in perspective. In the city district the largest difference is observed in footprint, when compared with the footprint of the centralized system: 23 mPt/m^3. As an average person uses about 50 m^3 of drinking water per year, the total difference amounts to 1,150 mPt per year. However, the total footprint of this person will be about 1,000 Pt per year, which means that the improvement amount to about 1‰ of the total footprint. For the single house the improvement is less, at even much higher costs.

As mentioned before, the footprint can also be calculated in kg CO_2. These results are shown in **Table 5**.

Obviously, the CO_2 footprint of the decentralized systems is significantly smaller than the footprint of the present process. However, if the additional costs are taken into account, the price per kg saved CO_2 is €12 for the city district, and €490-€560 per kg CO_2 for the single house. At the moment the price for emission rights is about €13 per ton [33]. These results show that in order to decrease the environmental impact rainwater harvesting in the Netherlands is not the most efficient way to achieve the goal.

5. Conclusions

Like for other sources of drinking water, rainwater can only be used as a source for drinking water when sufficient purification is applied. Especially the microbial safety of the collected rainwater is a point of concern in decentralized treatment systems and will require robust water treatment and frequent and expensive analyses to guarantee that the purification system still is working properly. The same applies to centralized drinking water treatment processes e.g. based on surface water, and in all cases identical analyses will be required to ensure water safety. However, as this will be required for each individual treatment process, costs will be relatively high for decentralized processes. Furthermore, in the Netherlands it will be difficult to harvest sufficient rainwater on an average roof to provide enough drinking water for the average family living below that roof. This problem may be solved by harvesting all rainwater from paved and built surfaces on a neighborhood level, under supervision of a drinking water utility. The fact that the production costs will be somewhat higher than the production costs for central drinking water may (partly) be compensated by the fact that less rainwater will have to be dealt with in WWTPs, and that less damage may be caused by heavy showers. However, there still are some practical problems that will have to be solved, like the storage of "dirty" and cleaned water, which requires a lot of space. Possibly, aquifer storage may solve this problem, but this will depend on the local situation.

The costs for rainwater harvesting and decentralized drinking water production strongly depend on the amount of water that has to be treated. If water is collected and treated for a whole district, the costs will be in the same order of magnitude as for centralized drinking water production. This will certainly be the case when possible savings, expressed as less nuisance during heavy rain showers, will also be taken into account. However, for a single house the costs are much higher than for the present centralized system.

Although the environmental impact will decrease by using rainwater as a source for the production of drinking water instead of surface water, the relative savings are very small. Besides, for this investigation only consumables were taken into account, not the impact of the installations and networks that will be required. This may affect the impacts.

The most important factor for rainwater harvesting in a densely populated city district, however, is that the amount of water that can be collected will be insufficient to provide enough drinking water to all inhabitants. Therefore, the general conclusion is that practically it will not be possible nor effective to implement rainwater harvesting for decentralized production of drinking water in densely populated areas in the Netherlands. However, the fact remains that in order to prevent problems caused by extreme showers due to climate change, rainwater will have to be collected. As it is a relatively clean source of water, it might as well be used for certain applications, and even the use as drinking water would be possible, when combined with alternative water sources. However, for safety and economic reasons this should be done at a relatively large scale (at least at neighborhood level) under the responsibility of drinking water utilities.

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