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Rainwater Harvesting for Drinking Water Production: A Sustainable and Cost-Effective Solution in The Netherlands?

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Abstract: An increasing number of people want to reduce their environmental footprint by using harvested rainwater as a source for drinking water. Moreover, implementing rainwater harvesting (RWH) enables protection against damage caused by increasing precipitation frequency and intensity, which is predicted for Western Europe. In this study, literature data on rainwater quality were reviewed, and based on Dutch climatological data the usable quantity of rainwater in the Netherlands was calculated. For two specific cases, (1) a densely populated city district and (2) a single house in a rural area, the total costs of ownership (TCO) for decentralized drinking water supply from harvested rainwater was calculated, and a life cycle assessment (LCA) was made. For the single house it was found that costs were very high (€60–€110/m^3), and the environmental impact would not decrease. For the city district, costs would be comparable to the present costs of centralized drinking water production and supply, but the environmental benefit is negligible ($\leq$1‰). Furthermore, it was found that the amount of rainwater that can be harvested in the city district only covers about 50% of the demand. It was concluded that the application of rainwater harvesting for drinking water production in the Netherlands is not economically feasible.

Keywords: rainwater harvesting; footprint; lifecycle analysis; total cost of ownership; sustainability; urban water management; drinking water

1. Introduction

Water utilities in the Netherlands observe a societal trend of an increasing number of people adopting a more sustainable lifestyle and showing willingness to make personal efforts to reduce their ecological footprint. Some of them consider rainwater harvesting (RWH) as one of the measures that could significantly contribute to a more sustainable way of living. Rainwater is thought to be clean and many people have the impression that rainwater is amply available in the Netherlands. As a result, drinking water utilities are increasingly confronted with customers wishing to live "off-grid", and to use rainwater for the decentralized production of drinking water.

Climate change will result in an increasing frequency and intensity of precipitation in Western Europe, and particularly in the Netherlands. It is also likely that the balance between dry and wet periods will change [1,2]. Existing urban drainage systems are based on a centralized approach, with drainage networks that transport wastewater and storm water run-off away from the populated areas. Urban drainage systems in the Netherlands are designed for a peak capacity of 20 mm rain in 1 h with a repetition frequency of once per 2 years. It is expected that the present drainage capacity will not be sufficient for future climatic conditions [1]. This will result in more frequent water at the street level and associated nuisance, damage to property, and increasing health risks [3]. A potential solution to cope with the effects of climate change is increasing storage capacity for rainwater in tanks or aquifers. This is common practice in parts of Belgium for new buildings and after home improvement [4]. In a recent study in Portugal, Bellu et al. [5] developed a framework model for a flood mitigation system based on detention basins, which could retain river water during a flood. Terêncio et al. [6,7] studied rainwater harvesting systems in the rural areas of the Ave River and Sabor River Basin in Portugal, for controlling excess flows and floods on one hand, and using the water for agricultural purposes in rural areas.

Collecting and storing rainwater in the urban environment also opens up opportunities for re-using the rainwater as an alternative source for water applications within the city. Many cities in the world already suffer water stress, and harvested rainwater can be an interesting supplemental water resource in these areas. Rainwater harvesting is gaining much attention in the international scientific community and among urban planners as an alternative source in integrated water resources management (IWRM) programs. Important examples are the "sponge cities" in China [8,9] and the large RWH initiatives in South Korea [10]. In Portugal, the dimensioning of a rainwater harvesting system was optimized for low demanding applications, where water availability largely exceeds water demand [11].

Many studies in international literature focus on the application of harvested rainwater for non-potable applications such as toilet flushing, washing machines and garden watering. Studies into rainwater quality and harvesting systems are described for the USA [12–14], Australia [15], Malaysia [16,17], Spain [18–20], South Korea [21] and Mexico [22]. In general, the conclusions were that the quality of the harvested water strongly depended on the type of roof material, the length of the preceding dry period, the application of a first flush and general environmental conditions. For application of harvested rainwater for drinking water production, it was found that a robust disinfection treatment is required [12,15,17,18].

In the Netherlands, there is little experience with rainwater harvesting, as the availability of fresh water has not yet been a problem. However, water utilities are increasingly confronted with customers who want to decrease their environmental impact by preparing drinking water from rainwater. Individual households may collect rainwater and use it for toilet flushing, but already in the 1990s the safety of harvested rainwater was considered a point of attention [23,24]. In order to study the effects, some large scale pilot investigations were carried out. At the moment, the Dutch drinking water law does not allow the use of harvested rainwater for applications other than toilet flushing. This prohibition was set in 2003, after hundreds of people became ill after drinking low-grade household water, as a result of cross-connections between the drinking water and household water network in one of the pilots [25,26]. In the Netherlands, only one quality of water is distributed, which is used for all (potable) applications. The Dutch water sector has a proactive attitude towards societal trends and their effect on delivered water services, and therefore has initiated research with a focus on three specific questions: (1) what is known about rainwater quality in the Netherlands and/or Europe, (2) does the amount of rainwater that can be harvested cover the local drinking water demand, and (3) what are the costs, economic benefits and environmental impact in comparison with the centralized conventional drinking water supply?

In this paper a feasibility study was described for the production of drinking water from harvested rainwater in two Dutch situations: a densely populated city district area and a single house in the rural area. We describe the results of a literature study on the quality of harvested rainwater, as there are only limited data available for the Dutch situation. The water quality data found in literature were used to propose a robust water treatment that would be required to guarantee the production of safe drinking water. In case such a treatment process would actually be built, experimental data on water quality would have to be gathered to determine the optimum treatment process. In this study, the quantity of rainwater that can be harvested in the Netherlands was determined. For two specific cases, a city district and a single house in a rural area, the total cost of ownership (TCO) for decentralized drinking water supply from harvested rainwater was calculated. Furthermore, a life cycle assessment (LCA) was made for both situations. Other applications than drinking water were not taken into account within this study.

2. Methods

A literature study was carried out on rainwater quality, as only very limited data are available for the Dutch situation. With respect to quantitative aspects, data of the Royal Dutch Meteorological Institute (KNMI) for the Netherlands between 2006 and 2016 were studied [27] and combined with data on the average use of drinking water [28].

Six different scenarios were studied, two for the city district and four for the single house. Details of these scenarios are shown in Table 1. All scenarios were based on either reverse osmosis (RO) or advanced oxidation (UV/H_2O_2). In this way a double disinfection barrier was realized in order to be able to guarantee safe drinking water. For the city district it was assumed that water would be collected in an open pond, but as a large open pond near a single house may not be practical, scenarios with either an open pond or a closed tank were calculated.

The dimensions of the ponds and collection and storage tanks were estimated based on the assumptions that it would have to be possible to collect two heavy showers within 24 h, and that sufficient drinking water should be available to cover a period of 6 weeks of drought period.

The total costs of ownership (TCO) method calculates the total capital costs and operational costs for a chosen evaluation period (TCO = investment costs + operating costs + maintenance costs + residual value). In this case, a period of 20 years was taken into account with an interest rate of 1.5%. For the cost calculations, a handbook for the calculation of small treatment processes was used [29]. Detailed information of the process steps, investments, building, energy, chemical costs, and so on are shown in Table S1 in the supplementary information. According to the model, the uncertainty in cost calculations is about 30%. This was determined by validation of the model with real capital and operational costs of a large number of full scale installations for drinking water production in the Netherlands that actually have been built and are in operation. A life cycle analysis (LCA) can be used to determine the environmental impact of urban water systems [30] and water treatment processes [31–35]. An impact calculation was made by applying SimaPro 8 software, applying the ReCiPe endpoint (E) [36] and impact data from the EcoInvent 3.0 database for consumables (i.e., energy and chemicals). In this way, results were obtained covering a wide range of environmental impacts, including climate change effects on ecosystems and human health, fossil and metal depletion, human toxicity, terrestrial, marine and fresh water ecotoxicity, particulate and chemical oxidant formation, urban and agricultural land occupation and natural land transformation. All impacts have been weighed by a panel of experts resulting into one single score expressed in ecopoints per functional unit, with the total yearly impact of one western European person being about 1000 ecopoints [37]. In this study, the functional unit was 1 m^3 of produced drinking water. Effects were calculated for both a small scale and a larger scale installation, and for different types of processes. As such, the results can be regarded as a sensitivity analysis on both scale and type of process.

Table 1. Six rainwater harvesting scenarios. Scenarios 1 and 2 for city district, scenarios 3–6 for single house. RO = reversed osmosis, CT = contact time.

Process Step	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
1	Collection of rainwater from paved and built surfaces	Collection of rainwater from paved and built surfaces	Roof surface area 235 m^2; grid (4)	Roof surface area 235 m^2; grid (4)	Roof surface area 140 m^2; grid (4)	Roof surface area 140 m^2; grid (4)
2	Open pond, 14×10^3 m^3 concrete (1)	Open pond, 14×10^3 m^3 concrete (1)	Closed HDPE(5) tank, 12 m^3	Closed HDPE tank, 12 m^3	20 m^3 open pond, concrete (1)	20 m^3 open pond, concrete (1)
3	Pumping (Grundfos CR 15-05) 10 m^3/h	Pumping (Grundfos CR 15-05) 10 m^3/h	Pumping 1.25 m^3/h (Grundfos CR1-7)	Pumping 1.25 m^3/h (Grundfos CR1-7)	Pumping 1.25 m^3/h (Grundfos CR1-7)	Pumping 1.25 m^3/h (Grundfos CR1-7)
	RO, membrane area 400 m^2, recovery 90%, 7.3 m^3/h	Sand filter height 2 m, 1.3 m^2; 3000 kg of sand	RO, Membrane area 40 m^2, recovery 90%, influent 1.11 m^3/h,	Sand filter height 1.5 m, 0.167 m^2; 650 kg of sand	Bag filter, pore size 25 µm	Bag filter (van Borselen X100), pore size 25 µm
4	Conditioning over calcite (2)	UV/H_2O_2 process (reactor with 4300 W LD UV lamps) 10 mg H_2O_2/L	Conditioning over calcite (2)	UV/H_2O_2 process (reactor with 120 W LD UV lamp Hereaus NNI 125-84-XL) 10 mg H_2O_2/L	RO, 5 µm sediment filter, two 5 µm AC filters; RO recovery 25%	UV/H_2O_2 Process (reactor with 120 W LD UV lamp Hereaus NNI 125-84-XL) 10 mg H_2O_2/L
5	UV disinfection (reactor with 120 W LD UV lamp Hereaus NNI 125-84-XL)	Activated carbon (CT = 20 min.); height 2 m, 1.65 m^2, 1320 kg of carbon	UV disinfection (reactor with 120 W LD UV lamp Hereaus NNI 125-84-XL)	Activated carbon (CT = 20 min.); height 1.5 m, 0.165 m^2, 99 kg of carbon	APEC in-line remineralization filter	Activated carbon filtration (6) (van Borselen VB06BE005-090DP)
6	Storage, 2 vessels (3), 5000 m^3 each, absolute filter.	Conditioning over calcite (2)	Storage, two 20 m^3 HDPE vessels with absolute filter.	Conditioning over calcite (2)	UV disinfection (reactor with 120 W LD UV lamp Hereaus NNI 125-84-XL)	Addition of $CaCO_3$ to increase pH
7	Treatment and disposal of RO concentrate	UV disinfection	Treatment and disposal of RO concentrate	UV disinfection	Addition of $CaCO_3$ to increase pH	Storage in 2 m^3 HDPE tank, absolute filter
8	Storage, 2 vessels (3), 5000 m^3 each, absolute filter.		Storage, two 40 m^3 HDPE vessels with absolute filter.	Storage, 2 vessels (3), 5000 m^3 each, absolute filter.	Storage in 2 m^3 HDPE tank, absolute filter (van Borselen BorsoPTFE BPF17SP002)	UV disinfection
9					Treatment of RO concentrate	

(1) Made of concrete, to prevent leakage of water in or out of the pond. (2) Using calcite from the softening process during centralized drinking water treatment. (3) Single coated steel buffer vessels, equipped with absolute filter. (4) Grid to remove branches, leaves, etc. (5) High Density Polyethylene (6) Removal of excess H_2O_2 and possibly formed byproducts and assimilable organic carbon (AOC).

The CO_2 footprint was calculated using the "single issue, greenhouse gas protocol" according to the international greenhouse gas protocol of the UNFCCC (United Nations Framework Convention on Climate Change) [38]. The CO_2 footprint (expressed as CO_2 equivalents = kg CO_2/m^3 drinking water) is calculated as the sum of fossil and biogenic CO_2 emissions and CO_2 from land transformation minus the CO_2 uptake. For the LCA, only consumables were taken into account, as it would be impossible to compare the impacts of buildings, installations and networks that differ in age by many decades and have been made from several materials. Consumables partly refer to the use of energy for pumps, membrane installations, and UV reactors. Here, we assumed that green energy (wind energy: electricity high voltage [NL] | wind, <1 MW turbine, onshore | Alloc Def S) was used, as all drinking water utilities in the Netherlands already use green energy. Furthermore, the use of chemicals and other compounds (activated carbon, sand, $CaCO_3$, H_2O_2, antifouling agents, etc.) were considered. The impact of all parameters was obtained from the EcoInvent database. The LCA included only consumables, such as energy, chemicals and materials (NaOH, HCl, CO_2, $CaCO_3$, H_2O_2, activated carbon, sand, etc.). Installations, buildings and networks were not taken into account. The impact of the centralized drinking water production was calculated from the following process [39]:

Water intake, coagulation by means of $FeCl_3$ and NaOH, sedimentation, filtration, infiltration, rapid sand filtration, ozonation, softening (by adding calcite and NaOH), pH correction by addition of HCl, filtration over activated carbon and aeration, addition of NaOH, and slow sand filtration. The total installed production capacity of the production site in Amsterdam was 12,000 m^3/h.

3. Results and Discussion

3.1. Rainwater Quality

In the Netherlands little data are available on rainwater quality, and therefore a literature search was carried out for quality data in other countries. In water, two types of contaminants can be distinguished: (a) chemical (either dissolved or suspended) and (b) microbiological. The uptake of contaminants occurs from the moment the raindrops leave the clouds. According to Grömping et al. [40], over 90% of atmospheric contaminants are removed by means of wet deposition. Although many ions present in rainwater are of natural origin (e.g., sodium, calcium and chloride) there also are anthropogenic contaminants like sulphate, nitrate, phosphate, ammonium, traces of iron, copper, cadmium, manganese, lead, zinc, nitrite, bromate and fluoride [41–48]. Concentrations are generally low, and in most cases below the Dutch standards for drinking water [49]. A comparison between some literature data [13] and both Malaysian and Dutch drinking water standards is shown in Table S2 in the Supplementary Information. In Tables S3–S6, analytical data from various countries in the world are summarized. The Dutch situation would be comparable to the situation in surrounding European countries like France (Paris city center and Île de France, department Ain, Seine Maritime in Normandy and a rural village), Ballinabrannagh in Ireland, Exeter in the UK and Bayreuth, Germany [50]. From the data it can be concluded that the variation in water-quality data in a certain area is similar in general to the variation between data from different areas all over the world. Furthermore, it can be concluded that for certain parameters, like heavy metals, treatment would be required, depending on local standards. The contents of iron, manganese and zinc in harvested rainwater may well be too high, but to which level concentrations would have to be decreased would be dependent on local legislation. In Malaysia, the standard for iron is 300 μg/L, whereas in the Netherlands this is 200 μg/L. On the other hand, the Malyasian standard for copper is 1000 μg/L, which is lower than the Dutch standard of 2000 μg/L. In comparing international treatment processes for harvested rainwater, it should be kept in mind that differences in local standards would affect the proposed treatment processes. In most investigations, inorganic compounds were measured, but Cindoruk and Ozturk [51] showed that organochlorine pesticides can be found in rainwater in several places in the world, and the presence of polycyclic hydrocarbons was demonstrated by Göbel et al. [52] and Angrill, Petit-Boix, Morales-Pinzón, Josa, Rieradevall and Gabarrell [18]. An overview of the concentrations generally found in rainwater is shown in the Supplementary Information Tables S3–S8.

Problems with water quality mainly arise from contamination during the collection of water, when the rainwater is in contact with hard surfaces. These surfaces are often covered with contaminants from dry (e.g., dust) and wet precipitation (rain, fog, snow, etc.), animal urine and feces and plant debris, which end up in collected rainwater [14,17]. Also, because of the often acidic character of the water, metals and carbonate from roof material may dissolve [48,52,53]. As a result, the quality of the water collected from roofs is generally 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), and the angle and direction of the roof [50]. An overview of physico-chemical parameters and concentrations of ions, heavy metals and microbiological parameters in harvested rainwater is given in the Supplementary Information Tables S3–S8. In general, the pH ranges between 6 and 9, and TOC concentrations are low (mostly $\leq$ 10 mg/L, sometimes 10–20 mg/L), although sometimes, like in Ain in France, high values up to 8800 mg/L are reported (see Table S5 in the Supplementary Information). The inorganic content (Cl^-, Na^+, SO_4^{2-}, NO_2^- and NO_3^-) of harvested rainwater is also low, and all data are far below the standards for drinking water. Table S7 shows the concentrations of a number of heavy metals in harvested rainwater. These may occur from the settling of aerosols on the roof and dissolution of roofing and water collection materials. Most values in Table S7 are well below drinking water standards, except for the lead concentrations, which may exceed drinking water standards.

The microbial contamination of water is especially a problem if the water is to be used as drinking water, as shown in Tables S2 and S8. As this problem occurs in all rainwater harvesting systems, it can be assumed that also in the Netherlands adequate disinfection would be required. In many cases, the number of bacteria (strongly) exceeds the standards for drinking water. Health risks appear to be related to bad material selection and maintenance of the rainwater harvesting system. If the wrong material is selected for the roof and plumbing, either heavy metals may dissolve into the water, or microorganisms may be able to grow on it. Regular cleaning of the equipment would prevent the presence and growth of microorganisms. Two sources of contamination have to be distinguished: (1) direct contamination of the harvesting surface and system, and (2) regrowth of bacteria in the storage tank. A robust disinfection is a prerequisite for use as a source for drinking water [12,15,17,18]. According to an investigation by Boogaard and Lemmen [54], similar results were obtained for collected Dutch rainwater.

In order to improve the quality of harvested rainwater, a "first flush" could be applied, in which the first amount of rainwater is disposed of, as this contains the highest concentrations of contaminants [17,20,21,45,50,55,56]. How large the first flush should be would depend on the situation; the type and location of the roof have an effect, but also the length of the antecedent dry period, as during this period contaminants accumulate at the roof. In general the first 0.1 to 3.8 mm (for horizontal roofs covered with gravel) have to be disposed of to reach a good quality [14,17,20,21,45,48,50,55,56].

As literature data from Europe and densely populated areas show large similarities, it can be assumed that the quality of harvested rainwater in the Netherlands would be similar to the qualities described in literature. This means that for drinking water applications, a robust treatment, especially disinfection, would be required.

3.2. Quantity of Rainwater

Data of 25 meteorological weather stations and 325 stations for deposition measurements across the Netherlands, gathered between 2006 and 2016, were studied [27]. During this period the yearly amount of rain increased from 814 mm to 856 mm due to the occurrence of more heavy showers. The amount of water that can be harvested depends on the run-off coefficient: the ratio of rainwater that can be harvested to the total amount of rainwater that falls on a roof. This factor depends on the type and angle of the roof, the dominant wind direction, the intensity of the showers and the amounts of water that are "lost" as a result of evaporation or leakage. The run-off coefficient varies between 0.7 and 0.95, with an average value of about 0.8 [20]. If both the run-off coefficient and a first flush of 2 mm are applied to the deposition data, the percentage of rainwater that can actually be harvested appears to be about 50%, as shown in Table 2. The data in Table 2 refer to the weather stations shown in Figure 1. For these calculations, all showers with rainfall below 2 mm (the first flush), were not taken into account. The total amount of rainfall appeared to be practically the same over the whole country. In some parts of the country, like Nieuw Beerta, however, relatively more small showers occurred, as a result of which a larger part of the total rainfall was discarded. However, in general it was concluded that the differences in type of rainfall over the country were small.

Table 2. Part of rainwater that could effectively be harvested, calculated for weather stations across the Netherlands, as shown in Figure 1.

Location in the Netherlands (City)	% of Rainwater that Could Effectively Be Harvested
Vlissingen	48
De Bilt	51
Maastricht	49
Twente	48
De Kooy	48
Nieuw Beerta	46
Average	48

Figure 1. Weather stations across the Netherlands.

In the Netherlands, the average roof surface is 60 m^2, and the average house is inhabited by 2.2 persons [57,58]. On average, a Dutch person uses 119 L of drinking water per day, or 95.6 m^3 per family per year (see Supplementary Information Table S9) [28]. If the first flush is disregarded, about 41 m^3 may be harvested on 60 m^2 of roof surface, which is far from enough to cover the total water demand of about 95.6 m^3. Besides, part of the summer rainfall occurs in large showers (requiring relatively large collecting tanks), which alternate with periods of up to six weeks of drought. This means that it is important that the capacity of the pond or basin is large enough to collect the large showers, but also that the storage basins for treated water are large enough to bridge periods or drought, depending on the season. Water saving showerheads, taps and toilet cisterns are common in the Netherlands and already contribute to the reduction of water use. Further decrease of the water demand could be achieved by active systems such as vacuum toilets and recirculation showers, but these are still very expensive. To come into the range of a water supply fully based on rainwater harvesting, a further radical reduction of water consumption is necessary. For instance, by applying a waterless toilet, a saving of approximately 29% of the water demand could be achieved, and another 25% reduction of water demand for showering would be necessary to enable self-sufficiency. Both measures would lead to a total water demand of 72 L/p/day, which could be covered by RWH.

From the above it is concluded that rainwater harvesting for an average Dutch dwelling is not providing enough water to realize a self-sufficient drinking water supply system.

3.3. Sustainability and Cost-Effectiveness of Rainwater Harvesting in the Netherlands

The preceding paragraph showed that the amount of rainwater that can be harvested on Dutch roof tops is not sufficient to cover the drinking water demand in general. However, to explore the possibilities in more detail, costs and environmental impact of rainwater harvesting were calculated for two cases:

1. A new city district, being developed in urban Amsterdam, considering all rainwater from paved and built surfaces, in order to also decrease negative effects from heavy showers, like flooding, and overcharge of the sewer system.
2. An individual house in the peri-urban area of Amsterdam, assuming that in this case the roof area would be large enough to cover the drinking water demand of the inhabitants.

For the city district the calculations were based on city government's plans for layout of the area [59]. The surface area of the new district, which is to be located on an artificial island in the IJ lake, is 13,000 m^2, and will comprise 1300 unit (partly single houses, partly apartment buildings). As probably the total roof area would be too small due to the presence of multi-story apartment buildings, it was assumed that rainwater from all built and paved surface areas could be harvested (a best case scenario). According to literature, the quality of this rainwater still should be better than the quality of surface water, which may contain wastewater treatment plant effluent [18]. This effluent in general still contains pharmaceutical residues, microbial contaminations, etc. The total built and paved surface area in this district is expected to be 93,600 m^2. Based on the meteorological data and an average run-off coefficient of 0.8, approximately 685 mm of rainfall could be harvested. Thus, it can be calculated that a maximum of 64,000 m^3 of water may be harvested in this district, collecting all rainfall on paved and built surfaces. This amount would cover about 51% of the drinking water demand of the planned number of inhabitants at the current rate of water use.

Combining rainwater harvesting with the regular central drinking water production and distribution as a backup system would solve this problem. However, in order to be able to deliver sufficient water at any moment (including periods with a shortage of rain and empty rainwater storage tanks or reservoirs), the capacity of the treatment process and network would have to be identical to a regular system. As a result, no savings could be realized on investments for central drinking water treatment, but the water volume produced by the central system on average would be smaller due to the use of rainwater harvesting, resulting in higher costs per m^3 for the regular drinking water. A negative side-effect of this system would be that the residence time of water in the drinking water network would increase because the demand for centrally produced drinking water is low in times that decentralized rainwater harvesting could be used. This may result in a lower water quality [60]. Thus, a combination of a "regular" central network with decentralized rainwater harvesting system results in higher drinking water costs per m^3 and possibly lower qualities of drinking water.

For the second case, the individual house in the rural area, it was assumed the total roof area would be large enough to be able to harvest sufficient rainwater for the residents. Houses in the rural areas in general are larger, and often there are also outbuildings like barns and stables.

For both the city district and the single house, TCO were calculated (see Table S1 in the Supplementary Information). Two treatment processes, based on either reverse osmosis (RO) or advanced oxidation (UV/H_2O_2) were taken into account. This was done to have a double disinfection step, and to be able to remove any micropollutants that may have been present due to industry, traffic and possibly agricultural emissions. An additional requirement was that the produced drinking water had to be supplied without chlorine disinfection, similar to the current Dutch drinking water supply. Analyses results only become available after 24 h after potential contamination, meaning that, as water is consumed immediately after production, there is a risk that contaminated water would be consumed prior to the detection of the contamination. Therefore, it was decided that a robust treatment system is needed to deal with any pollutants that may occur, especially since water harvested from parking lots, pavements and roads would have to be treated. A detailed description of the total processes is given in Table 1.

For the city district, it was suggested to collect rainwater in an open pond. In a closed basin, water quality would become anaerobic and deteriorate quickly, as a result of which the water would have to be treated shortly after collection, resulting in a large treatment and storage capacity. With an open pond this would be less important, as water could be treated continuously over a longer period. Naturally, the water quality here too would deteriorate as a result of dust and contaminants from the surroundings, but the treatment process could be adjusted to this, as is the case with surface water used as a source of drinking water. In order to be able to harvest the maximum amount of water, and to prevent nuisance from heavy rainfall, the volume of this pond should be 14,000 m^3, or, at a depth of 4 m, it would require an area of about 3500 m^2, equaling about half the area of all sports fields and parks planned in the district.

For the single house, an open pond of 20 m^3 would be required, but it can be doubted whether the presence of such a large pond, which would be nearly empty during most of the year, would be desirable in the vicinity of a house. Therefore, we also calculated a situation in which water is collected in a closed tank. As untreated water cannot be stored for a longer period, and as the tank would have to be emptied within a short time (in order to be able to collect the next rain shower), the treatment capacity of the process would have to be relatively large in this case, although it would only be used occasionally. This would result in relatively high investment costs and operational costs of the system.

In total, six scenarios were studied, as shown in Table 1. In a case in which RO is applied as the main treatment process, the permeate would have to be conditioned in order to meet drinking water standards. As microorganisms may grow on the calcite filter used for conditioning, a second disinfection by UV would be required. For treatment processes based on a UV/H_2O_2 process, first rapid sand filtration is applied in order to obtain a first disinfection step and to remove particles and NOM (Natural Organic Matter), in order to improve the UV transmittance and turbidity of the water. Filtration over activated carbon is applied to remove the excess of H_2O_2 and any byproducts that may have been formed during the oxidation process. Conditioning is required to meet the drinking water standards for calcium. In order to remove any microorganisms originating from the carbon or calcite filters, a UV disinfection is applied afterwards.

For all scenarios, TCO and LCA were calculated. The results were compared to costs and environmental impact of centrally produced drinking water, with the use of surface water as a raw water source for the city of Amsterdam. Details of the TCO calculations are shown in Table 3.

Table 3. Details of TCO calculations of all six scenarios.

Scenario	1	2	3	4	5	6
Building costs (€)	1.44×10^6	1.43×10^6	6.02×10^4	4.54×10^4	1.83×10^4	1.83×10^4
Investment costs (€)	1.98×10^6	1.97×10^6	8.30×10^4	6.27×10^4	2.52×10^4	2.53×10^4
Interest & depreciation (€/y)	1.15×10^5	1.15×10^5	4837	3650	1469	1473
Operation & maintenance (€/y)	4.95×10^4	4.93×10^4	2076	1567	630	632
Energy (€/y)	713	3.96×10^4	3	123	2	123
Chemicals (€/y)	13	4355	0	1189	0	33
Membrane replacement (€/y)	1200	0	160	0	210	0
Filter (€/y)	50	5050	5	507	76	99
Lamps (€/y)	32	480	3	0	0	0
TCO (€/m^3)	2.71	3.43	85.24	84.76	38.27	38.02

The environmental impact of all scenarios was also calculated both in ecopoints and in CO_2 equivalents. This CO_2 footprint is often used, but it doesn't take into account all effects. As the LCA calculations are based only on consumables, the environmental impact for scenarios 5 and 6 equals the impact for scenarios 3 and 4, as these scenarios only differ in the type of collection tank (either a closed tank or an open pond).

In order to calculate the positive effects of rainwater harvesting (preventing nuisance and damage due to heavy rainfall) 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 hard surfaces. These taxes amount to €1.84/m^2 of paved surface area [61]. Therefore, it was assumed that a similar amount of money per m^2 could be saved in the Amsterdam area if rainwater were harvested and used as a drinking water source, instead of being discharged into the sewer. So for the calculation of the total costs, €1.84/m^2 was deducted from the production costs. The results are shown in Table 4. In order to be able to guarantee drinking water safety, regular analyses would be required. The yearly costs for water quality monitoring are on the average €2500. These costs would have to be made for every production plant, as a result of which the costs are very high for a single house (€25.93/m^3), but low for a district with more houses (€0.04/m^3). These costs have been included in the production costs in Table 4.

Table 4. TCO and LCA for scenario 1–6.

Scenario	Production Costs (€/m^3)	Analyses Costs (€/m^3)	Savings (€/m^3)	Net Costs (€/m^3)	Impact (mPt/m^3)	Impact (kg CO_2/m^3)
1	2.71	0.04	1.60	1.15	14.7	0.003
2	3.43	0.04	1.60	1.87	11.8	0.004
3	85.24	25.93	4.48	106.69	32.5	0.002
4	84.76	25.93	4.48	106.21	24.1	0.004
5	38.27	25.93	2.69	61.51	32.5	0.002
6	38.02	25.93	2.69	61.26	24.1	0.004
Centrally treated drinking water			0	1.63 (*)	36.4	0.130

(*) Price includes taxes, administration, etc. These costs would have to be added to the net price of scenarios 1–6.

The relatively high costs for small drinking water treatment systems are in accordance with literature findings. Roebuck et al. [62] studied 3840 domestic systems and concluded that harvesting rainwater was significantly less cost-effective than using only centrally produced drinking water. None of the RWH systems were able to demonstrate a return on investment. Although the operation of RWH appeared to be cheaper than drinking water, the periodic recurring costs for maintenance proved to be greater in magnitude than drinking water savings, resulting in a larger total rate. Domènech and Saurí [63] evaluated the use of RWH systems in the metropolitan area of Barcelona, Spain. In their study, they investigated social aspects, drinking water savings and costs of single- and multi-family buildings. For the economic modeling they also used the RainCycle model Roebuck used. For single-family homes, the harvested rainwater was used for toilet flushing, cleaning, filling the swimming pool or washing the car. In multi-family buildings, only garden irrigation was assumed. Again, in this study long payback times were found, up to 60 years with the main cause being high capital costs. Farreny et al. [64] investigated RWH on a larger scale in dense Mediterranean urban neighborhoods. The research compared cost-efficiency at two scales (single building and neighborhood) and implementation (new construction areas and existing area retrofits). However, the case study was limited to the use of rainwater for laundry washing only. The authors concluded that cost-efficiency of RWH strategies may be in doubt as long as local water prices are low. Furthermore, they concluded that RWH systems should be preferably installed at the neighborhood level, because of economy of scale. Installations should be realized in new construction areas to be cost-effective. Morales-Pinzón et al. [65] investigated 87 scenarios in a number of Spanish cities consisting of RWH systems of various sizes, ranging from two single houses to a group of apartment buildings connected to a single RWH system. They concluded that the material type used for a storage tank was not a fundamental financial factor, but planning on a neighborhood scale was. The costs per functional unit ranged from 0.94 to 10.59 €/m^3, with the lowest cost for the category "group of apartment buildings". RWH systems have a better financial fit for large-scale and high-density constructions. According to these authors, the best strategy was implementation at a neighborhood level. An example of such a system can be found in Ringdansen, Norrköping (Sweden) [66]. In these studies, too, it was concluded that the variability of rainfall is an important factor to be considered in detail during design because it has a direct impact on the RWH tank size.

In Table 4 it also can be seen that by only taking into account the CO_2 footprint, the difference between the scenarios is very small. Differences in effects, like those on human health or ecosystems, may not be fully accounted for when looking only at the CO_2 footprint, which makes up only part of the footprint in ecopoints. For example, scenarios 3 and 5 seem to have a low CO_2 footprint, whereas they have the highest footprint in ecopoints. The CO_2 footprint of the centrally produced drinking water is significantly higher, as the water has to be transported over a distance of about 60 km from intake to the treatment plant, and softening is applied. Furthermore, it is likely that the impact of filtration over activated carbon is higher in a large-scale process, as in such a scenario surface water is used as a source, which probably would contain more micropollutants, resulting in a higher reactivation frequency for the activated carbon.

These results are in accordance with literature data, where it was also found that the overall generated impact of water treatment is driven by the consumption of energy. When the impact of the installations is also included, a significantly higher total impact would be the result [33]. Some previous LCA studies at water utility Waternet showed that the most significant impact contributors of the centralized treatment process are the use of conventional energy, coagulation, softening and filtration over granular activated carbon [32,35]. As softening and coagulation don't have to be applied with rainwater, this lowers the environmental impact of the treatment process. Garfí, Cadena, Sanchez-Ramos and Ferrer [31] compared the environmental impacts caused by drinking water consumption in Barcelona, comparing centrally treated tap water from a conventional plant and from a plant based on RO, tap water treated with point-of-use RO, mineral water in plastic bottles and mineral water in glass bottles. The results showed that the centrally treated drinking water caused the smallest impact, the impact of domestic RO being 10–24% higher.

As with other sources of drinking water, rainwater can only be used as a source for drinking water when sufficient purification is applied, especially when water from all paved and built surfaces is used. The microbial safety of the collected rainwater is a point of concern in decentralized treatment systems, and would require robust water treatment and frequent and expensive analyses to guarantee that the purification system was still working properly. The same applies to centralized drinking water treatment processes (e.g., based on surface water), but, as less water would be produced, the costs per m^3 would be higher for decentralized processes. Apart from the high analysis costs, it would be very difficult to guarantee safe drinking water in decentralized systems, as the enforcement of measures that must be taken based on analytical data would be very difficult. Besides, monitoring would only give results after at least 24 h, while problems could occur immediately in decentralized systems. At present, no online monitoring is possible.

Taking into account the cost savings related to RWH as a result of less problems caused by heavy showers, the costs of decentralized drinking water production based on rainwater harvesting would be in the same order of magnitude as costs for centrally produced drinking water. For a single house, costs would be much higher. This is due to relatively high investment and analyses costs. Especially when water is collected in a closed tank, costs become very high due to the additional spare capacity required for enabling a rapid treatment of harvested water, which is necessary for emptying the collection tank for the next rain event.

Although the environmental impact seems to decrease by using rainwater as a source for the production of drinking water instead of surface water, the relative savings are very small. As one Dutch person yearly on average uses 43.4 m^3 of drinking water, a maximum of $43.4 \times 24.6 = 1068$ mPts could be saved, which is about 1‰ of the total environmental impact of this person. Besides, only consumables were taken into account for this investigation, not the impact of the installations and networks required. If these were also included, the impact of decentralized systems would increase compared to the impact of a centralized system, as a large number of small installations requires more material than one large scale installation.

Although from this study it can be concluded that production of drinking water from harvested rainwater in the Netherlands is far more expensive and doesn't really have a positive effect on the environment in comparison with the centralized production and distribution of drinking water, this doesn't mean that rainwater harvesting should not be applied. It is a proven tool for storm water management, and when rainwater has been collected, it might as well be used for certain applications, like industrial applications or maybe household water. However, using it as a source for drinking water is not recommended.

4. Conclusions

Based on literature data it is expected that the quality of harvested rainwater in general would not meet (Dutch) drinking water standards, and thus a robust treatment is required. The quality is strongly affected by the surface used to harvest the rainwater, and the microbiological quality often requires a robust disinfection in order to produce safe drinking water. For decentralized treatment systems, the required analyses result in high costs per m^3, and even then, it would be very difficult to guarantee water safety, as enforcement of required maintenance would be hardly possible on a small scale.

By considering only consumables, using rainwater as a source for decentralized drinking water production results in a slightly smaller ecological footprint compared to the use of surface water in a central system. However, this difference only results in a decrease of about 1‰ in the total environmental impact of a person per year. When the impact of the installations is also included, a significantly higher total impact results. The use of steel has an especially large contribution to the total impact. Besides, for the RO processes, the disposal and treatment of concentrate is another factor that should be considered in costs and environmental impact.

The costs of a decentralized drinking water production are (much) higher than the costs of a centralized water supply system. In order to make rainwater harvesting economically interesting, water should be collected on a neighborhood scale and not per individual building. To create a fully self-sufficient system, water not only from roof tops but also from paved surfaces should be harvested. By doing this, water nuisance during extreme weather events may be reduced, lowering the total societal costs involved (rainwater harvesting and treatment plus costs of storm-water management).

In densely populated areas, like the city of Amsterdam, the amount of rainwater that could be harvested is insufficient to cover the water demand of the inhabitants, even if water-saving measures are being taken. As a result, a centralized drinking water treatment system and network would still be required, in addition to the RWH system.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/3/511/s1: Table S1—TCO calculations for six scenarios; Table S2—comparison of composition of harvested rainwater and Malaysian and Dutch drinking water standards; Table S3—inorganic parameters in directly harvested rainwater; Table S4—heavy metals in directly harvested rainwater; Table S5—physico-chemical parameters in harvested rainwater; Table S6—inorganic parameters in harvested rainwater after first flush; Table S7—heavy metals in harvested rainwater after first flush; Table S8—microbiological parameters in harvested rainwater after first flush; Table S9—use of drinking water in the Netherlands in L/person/day in 2016.

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