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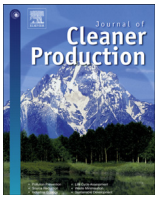

Performance assessment and life cycle analysis of potable water production from harvested rainwater by a decentralized system

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ABSTRACT

Decentralized rainwater harvesting (RWH) from roof runoff can complement the centralized supply of mains (drinking) water for a range of contexts, to assist in alleviating issues of water security. However, treatment to potable standard of harvested rainwater is not widespread. Consequently a comparative life cycle analysis (LCA) of decentralized and centralized potable water supply has not previously been undertaken. In this paper we describe a novel point-of-use (POU) treatment device, which was used to treat harvested rainwater to potable standard. We then provide a performance assessment for this system and an LCA with a comparison to centralized supply. Results of the performance assessment indicate a water saving efficiency (E_T) of between 0.6 and 100%, depending on rainfall (0.6 from April when rainfall was significantly below average). This highlights that the POU device was able to deal with the scale of roof runoff supply originating from a RWH system at a commercial building scale. The LCA results suggest that potable water produced from this decentralized RWH POU system currently performs more poorly than centralized water from an environmental perspective. Its impacts in most categories would be significantly reduced if the electricity consumed by the system were supplied from a renewable source such as solar PV or wind turbines instead of the UK grid. Priority should be given to optimizing the energy efficiency and exploring opportunities for combined use with renewable energy technologies in order to improve the environmental performance of POU treatment devices.

1. Introduction

Pressures on centralized water supply systems, such as climate change, urbanization, population growth and changing socio-economic conditions across the globe, have catalyzed interest in alternative approaches to ensuring water security. These include considering where such centralized infrastructure can be complemented with decentralized infrastructure, for example rainwater harvesting (RWH) systems. This is particularly noteworthy in countries with the potential to 'leap frog' the lock-in to centralized infrastructure systems that most 'Western' countries are experiencing and in doing so also consider the social practices, human capabilities and social relations that add further complexity to resolving water security issues (Jepson et al., 2017). RWH has been demonstrated as yielding multiple benefits as well as being an alternative water supply, with such benefits including stormwater attenuation, water autonomy and reducing energy consumption (Melville-Shreeve et al., 2016).

RWH is the collection and use of surface runoff, with roofs being the primary catchment area of choice due to limited contamination of the surface. Roof runoff is harvested via rainwater goods such as gutters and downspouts and stored in tanks, after which it is fed to various points of (usually non-potable) use, such as toilet flushing, garden irrigation, vehicle washing or in washing machines (Konig, n.d.). Over the last 10 years, there has been an upsurge in the volume of research on various aspects of RWH (Campisano et al., 2017) with a significant focus on feasibility assessments and cost-benefit analysis (Amos et al., 2016; Domínguez et al., 2017; Ghisi and Schondermark, 2013; Wang and Zimmerman, 2015) and increasing the efficacy of system configurations for different property types and end-user objectives (Melville-Shreeve et al., 2016).

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Additionally, there have been a number of LCA studies on RWH systems installed in different regions worldwide. For example, Morales-Pinzón et al. (2012) assessed a domestic RWH system for 3 different types of buildings at an urban scale in 16 cities in Spain and found the life cycle fossil energy use for the water delivered to range from 5.76 to 14.4 MJ/m^3 and greenhouse gas (GHG) emissions from 0.27 to 1.38 kg CO$_2$-eq/m^3. Ghimire et al. (2014) evaluated domestic RWH systems for a watershed in Virginia, USA and compared them with municipal water. Their results suggest RWH water outperforms municipal water in all environmental impact categories considered except Ecotoxicity, with life cycle fossil energy use and GHG emissions for domestic RWH water of 5.44 MJ/m^3 and 0.41 kg CO$_2$-eq/m^3, respectively, as opposed to 9.63 MJ/m^3 and 0.85 kg CO$_2$-eq/m^3 for municipal water. Ghimire et al. later analyzed a commercial RWH system in comparison with a municipal water system for Washington, D.C. (Ghimire et al., 2017). They found the RWH system outperformed the municipal water system in all impact categories except Ozone Depletion and energy usage was the dominant contributor to most impact categories for both systems. Vialle et al. (2015) assessed the environmental impacts of a domestic RWH system in France for toilet flushing and found that water delivered through the RWH system had slightly higher impact than that of mains water (potable drinking water originating from a centralized supply system). They also noted that when a disinfection step was included the environmental performance of the RWH system became highly unfavorable because of high electricity consumption. Angrill et al. (2017) examined RWH systems in Mediterranean regions and compared the environmental impacts of 24 system configurations with varying tank location, building height and demand distribution. They found tank location and distribution strategy were the most important variables in the optimization of RWH systems from an environmental perspective.

However, to the best of our knowledge there is no LCA study on *potable water* produced from RWH by decentralized systems and its comparison with mains water. In this paper, we aim to fill this gap by presenting the first comprehensive LCA on potable water produced from harvested rainwater by a point-of-use (POU) treatment system based on data collected from a field trial in the UK. We also present an overview of the performance of the novel POU treatment device used to treat the harvested rainwater to potable standard. Consequently, the paper will be of interest to researchers and practitioners working in the areas of water security, resilient cities, off-grid communities, hybridization of water systems and smart water futures. The paper proceeds as follows. The Material and Methods section briefly describes the treatment device and the techniques used to analyze its performance and the environmental impact of the potable water it produces. The following section then summarizes the results of the analyses and discusses their wider implications. The last section presents the main conclusions of the study.

2. Material and methods

2.1. System description

The decentralized treatment system trialed was a POU device developed by RainSafe Water (part of Ozone Technologies Ireland, an Irish water innovations and solutions company) that enables non-potable water (e.g. rainwater, well water) to be treated to meet potable (drinking, mains water) standards. By connecting a RWH system to this POU device, the harvested rainwater is treated to potable standard enabling it to be consumed as drinking water or for similar end uses (bathing, showering, cooking etc). Where mains water availability or quality is low or properties are off-grid, the POU device facilitates access to a readily available source of water (rainfall permitting).

The configuration of the POU device is illustrated in Fig. 1. Harvested rainwater is processed, with a range of monitoring and metering devices, first through a 5 μm inlet filter in preparation for treatment with ultraviolet (UV) light that attenuates biological contaminants. Ozone is generated and introduced into the 230-L water holding tank where it is stored - with the residual ozone providing sanitization, replacing chlorine. When water is required for use, it is pumped through a carbon outlet filter. Ozone and carbon also improves the taste of the water, with carbon also converting any remaining ozone back to oxygen and removing flocculated particles prior to the water being circulated.

2.2. Field trial and performance assessment

The field trial of the POU device was conducted in the Innovation Centre on the University of Exeter's Streatham campus, an office building servicing approximately 300 occupants, a café and conference facilities. Waterless urinals are used within the building. A RWH system is located within the building and used to flush toilets in order to reduce mains water consumption. The RWH system consists of catchment, conveyance, storage and redistribution sections (Fig. 2). The catchment and conveyance section consists of a south-facing roof catchment (1500 m^2) that has both aluminium and bitumastic-felt-membrane sections and powder-coated aluminium rainwater goods (guttering and downpipes). The storage and redistribution section consists of a glass-reinforced plastic underground storage tank (25 m^3), a control system, two glass-reinforced plastic header tanks (0.8 m^3 each) and associated medium-density-polyethylene and copper pipework. There is also three-tiered filtration system, consisting of a 440-μm pre-tank coarse debris filter, a 180-μm in-tank floating suction filter and a 35-μm inline backwashing filter. The backwashing filter provides the highest level of filtration for the harvested rainwater, as well as automatically backwashing to prevent clogging and maintain performance. It should be noted that there is no first flush device fitted to the system. Roof runoff was diverted to the west header tank during the field trial and therefore all harvested rainwater was supplied only the toilets in this wing of the building – serving around 100 people, plus the café and conference facilities. The POU device attached to the RWH system at the University of Exeter test site used UV and ozone treatment and only supplied water for toilet flushing. However, the water produced was potable quality and therefore could potentially be used for other purposes such as drinking and washing in the building where it was installed. Ward et al. (2017) present the results of in depth water quality testing for this POU device at the Exeter field trial site, as well as additional sites in Ireland and Germany. The LCA presented in the current paper focuses only on the Exeter system as this is the only site where energy consumption data is available. However, across all the sites, as reported in Ward et al. (2017), the POU device was able to reduce levels of microbiological and pathogen parameters in delivered water to meet UK, EU and WHO potable standards where harvested rainwater did not contain elevated pesticide or physicochemical levels. The device attained reduction to potable standard of microbiological determinants, such as total viable counts and coliforms and full removal of pathogens including *Pseudomonas aeruginosa* and *Legionella* spp. These results highlight that it is possible to treat harvested rainwater to potable standard, but the LCA implications of such usage require investigation to examine whether this option is feasible from a broader environmental impact point of view. Consequently, an LCA of the system was undertaken.

Data (for parameters such as volumes processed, average flow

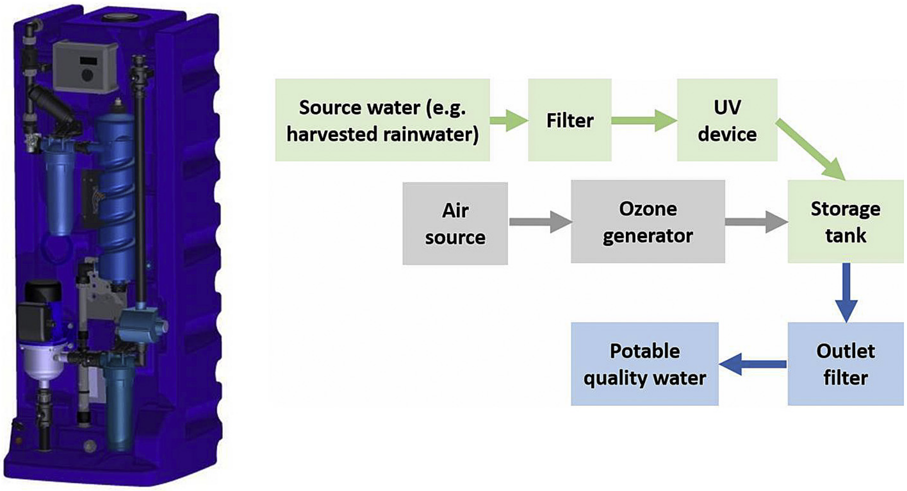

Fig. 1. Real-world and schematic configurations of the POU treatment device (top left to bottom right: control panel, filter, UV/ozonation, copper-silver, pump, filter; storage tank shown at back).

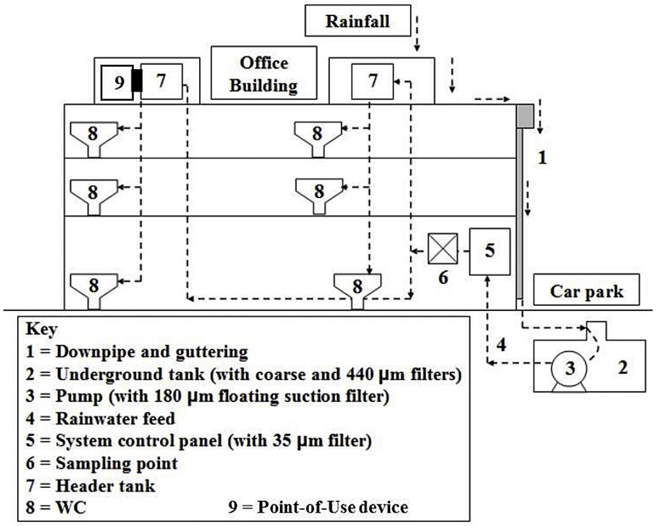

Fig. 2. Configuration of the RWH POU treatment system in the Innovation Centre building.

rates, duration of ozonation etc) was logged by the POU device itself and collated remotely using standard Wi-Fi transmitters and router ports. The system was commissioned on 24th February 2015 and data generated between 25th February and 31st December is considered in this paper. This data was subsequently used to assess the performance of the POU device through a water quantity analysis, which focused on:

- Reduction in centralized water demand (m^3);
- Potable water delivery to regions of low centralized supply (savings in bottled water per annum);
- Water saving efficiency (WSE, E_T).

In relation to the second indicator, a bottled water volume of 19 l (0.019 m^3) was used as a comparison, as this appears to be the industry standard volume (for a non-mains water cooler). Whilst there is limited publically available information regarding bottled water consumption patterns at different scales, one source quotes a residential setting with two adults and two children would consume 25–38 bottles per year (Megan Lane, 2003), which is used as a starting point for comparisons in the following analyses. For water saving efficiency the approach outlined in Ward et al. (2012) was used. E_T is the volume of drinking (mains) water supplemented by harvested rainwater – or in this case, treated rainwater and is a percentage measure of mains water conserved in relation to total demand. It is calculated by dividing the volume of rainwater consumed by the total demand for water, as follows:

$$E_T = 100 \times V / D$$

where, V is volume of rainwater consumed (m^3) and D is total demand (m^3). Where the harvested rainwater only supplies a certain number of end uses, for example for toilet flushing only (as in the Innovation Centre), the calculation required is:

$$E_T = 100 \times VWC / DWC$$

where, VWC is volume of rainwater consumed by the toilets (m^3) and DWC is total toilet demand (m^3) (Ward, 2010).

2.3. Life cycle analysis method

The goal of the LCA is to evaluate the environmental impacts of potable water produced using the decentralized RWH POU system in comparison with that from centralized supply. The system boundaries of the LCA are cradle-to-gate, i.e., all the upstream processes will be considered up to the point of delivery of potable-quality water to end users. The main life cycle stages for water produced by the decentralized system include the manufacturing, operation and maintenance and disposal of the POU device while those for centralized water include water infrastructure, water treatment and water distribution. The functional unit is chosen to be 1 m^3 of potable-quality water delivered to end users. The LCA software SimaPro 8.0 (PRé Sustainability, 2016) is used for the modelling. The widely used ReCiPe Midpoint life cycle impact assessment (LCIA) method (Goedkoop et al., 2013) was chosen for the impact assessment, which considers 18 different impact categories. The life cycle inventory (LCI) data was based on the POU device tested in the field trial. The foreground data was collected from the supplier RainSafe Water and the field trial, while some background data such as materials used in manufacturing and electricity consumed in operation was taken from the ecoinvent v3 database available within SimaPro.

The materials consumed in the manufacturing stage were estimated based on a detailed component break-down of the POU device. These were grouped into 7 material categories including plastics, metals, glass, ceramics, fibre, chemicals and paper as well as 3 component categories including printed circuit board (PCB), pumps and cables. The reason the PCBs, pumps and cables were not further broken down into different constituent materials was that these were off-the-shelf components and the details of the materials used were not available. However, there were background datasets available in ecoinvent for the manufacturing of these components and therefore they were used in the modelling. Some of the components have more than one type of material, e.g., the control board (371 g) consisted of PCBs and plastic housing and the ozone free lamp (97 g) consisted of glass, plastics, and metals. In these cases, the materials break-down was estimated based on the authors' engineering expertise and unspecified metals were assumed to be iron. The final materials and components break-down used in the LCA model is shown in Table 1. There were a few materials that were not available in the ecoinvent database and these were therefore disregarded. They accounted for only 0.1% of the total weight of the POU device so this should not affect the results in any significant way. The electricity consumed in the assembly of the POU device was assumed to be 50 kWh, with the background ecoinvent dataset used being Low Voltage Electricity in Ireland. The lifetime of the POU device was assumed to be 12 years.

The operation and maintenance stage considers the electricity consumed in normal operation of the POU device. Engineer visits for servicing and repair were not considered due to lack of data. Annual water delivered was estimated to be 225,115 L based on a linear extrapolation of the water flow through the POU device logged during a continuous 335-day period from 24th February 2015 to 25th January 2016 (206,612 L during this period). Electricity use was monitored during a 6-week period from 1st February 2016 to 13th March 2016. Electricity use per m^3 water delivered was 5.55 kWh based on the total electricity use of 130.2 kWh and the total volume of water delivered 23,449 L during the monitoring period. Four electricity scenarios were explored to assess the effect of different electricity sources on the final environmental impacts: current grid electricity, electricity generated from rooftop solar photovoltaic (PV) panel, electricity generated from onshore wind turbine and grid electricity in 2030. The UK grid mix in 2030 was based on the Gone Green scenario in National Grid's forecast (National Grid, 2015). The disposal stage follows the waste treatment scenario for the total waste of England readily available in SimaPro.

Table 1
Materials and components break-down of the POU device used in the LCA.

Material	Weight (g)
aluminium	1371.50
stainless steel	1615.50
brass	143.00
copper	50.00
silver	50.00
Zinc	1.00
unspecified metal	468.35
ceramic	534.50
paper	375.00
cardboard	10,000.00
cellulose fibre	92.00
glass	158.50
plastic	7731.75
plastic PE	34,312.00
plastic PVC	897.00
plastic, PET	1316.00
plastic, polycarbonate	125.00
plastic, PP	178.00
plastic, PTFE	6.00
plastic, nylon	3.00
plastic, PUR	1.00
rubber	58.50
silicone	98.50
aluminium oxide	380.00
epoxy resin	10.00
carbon	84.60
PCBs	545.50
pumps	12,542.00
cables	217.00

For water from centralized supply, the readily available ecoinvent dataset for Swiss municipal water production and supply was adapted to UK conditions by replacing the Swiss grid electricity with the UK grid electricity. This dataset included the construction of infrastructure such as water works, water supply network, water storage and pump station and the manufacturing of chemicals used such as hydrogen peroxide, aluminium sulphate, chlorine and ozone. Water abstraction is considered to be 0.41 m^3 from ground water, 0.21 m^3 from reservoirs and 0.51 m^3 from rivers for every 1 m^3 of water delivered to end users.

3. Results and discussion

Firstly the results of the performance assessment are presented and then a detailed account of the LCA is provided.

3.1. Performance assessment

The average monthly water processed profile is summarized in Fig. 3. A low volume of water was processed and supplied in February due to the date of system commissioning, in April due to low rainfall and in October due to system downtime as the result of lag times between issue diagnosis (clogged filter) and resolution.

The total volume supplied (i.e. reduction in centralized water demand or wastewater volume) across the monitoring period (315 days) was 191 m^3. The maximum daily volume processed and delivered into supply was 2.7 m^3 on the 23rd November 2015, with the minimum being 0 m^3 across a range of dates when the Innovation Centre was unoccupied (e.g. weekends). 191 m^3 is equivalent to approximately 47,708 4-L toilet flushes and 31,805 6-L toilet flushes, respectively. Given an occupancy of approximately 100 for the west wing of the building, this equates to at least one 4-L flush per day and a daily average of 51 4-L flushes for the café and conference area, which is reasonable (as there are also waterless urinals). If supplied through the mains water network by the local

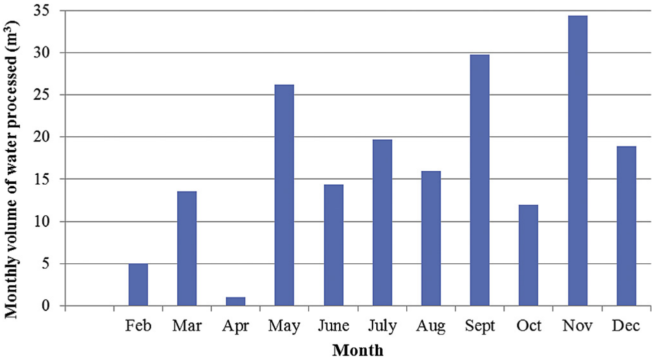

Fig. 3. Monthly volume of water processed by the Exeter RWH POU system.

water utility (South West Water, n.d.), this volume would have incurred a water supply charge of £374 (based on a non-household tariff of £1.96 per m^3, not including VAT or the associated annual charges as the latter depends on the number of meters a non-household customer has).

In relation to savings in bottled water per annum (or in this case per 315 days), if the 191 m^3 of water was used for drinking this would equate to approximately 10,044 bottles (enough to supply between 200 and 400 families). At a cost of around £6 per bottle (Wingham Well Spring, n.d.), this would result in a total bottled water supply cost of £60,262 (this does not include the 'sanitization service' charge of £12.50 per quarter). In relation to carbon emissions, which were estimated using another bottled water company's 'carbon calculator' (0.03 kg CO_2 per 20 cl or 150 kg CO_2/m^3) (Eden Springs, n.d.), this number of bottles would result in a carbon emission of 28,650 kg CO_2 (28 t). This figure is compared below with those reported in the LCA for carbon emissions associated with the POU device operation.

Regarding WSE, unfortunately, the Building Monitoring System for the Innovation Centre only recorded the total building mains water consumption, though for the RWH supply the data was recorded for both the East and West header tanks. This required an estimation to be made of the percentage of the total building mains water consumption that could be attributed to toilet flushing. After a literature search, a figure of 87% was derived (Mohamed Chebaane and Bill Hoffman, n.d.) for office buildings such as the Innovation Centre. Table 2 summarizes the calculations for the POU device, showing that a monthly E_T of between 0.6 and 100% was achieved, depending on rainfall (0.6 was from April when rainfall was significantly below average).

This, combined with the flow analysis presented previously, highlights that the POU device is able to deal with the scale of supply originating from a RWH system at a commercial building scale. Had greater volumes of harvested rainwater been available, the WSE would have been higher, as the POU device would still have been able to process the water. This indicates that given a sufficient supply of harvested rainwater in a residential setting, the POU device would potentially be able to meet all potable demand (i.e. not just toilet flushing). However, it is important to consider the environmental impact that the decentralized supply of this potable water might have. Consequently, a LCA was performed and the results are provided in the next section.

3.2. Life cycle analysis results

The LCIA results are shown in Table 3 and Fig. 4. The carbon footprint of centralized water was found to be 0.44 kg CO_2-eq/m^3, which was within the range of 0.3–0.5 kg CO_2-eq/m^3 that most UK water companies lie in according to the Water UK Sustainability Indicators 2010/11 (Water UK, 2012). It can be seen that if the electricity used during operation is drawn from the current UK grid, potable water produced from the decentralized RWH POU system results in higher impacts than that from centralized supply for all 18 impact categories considered. These range from 60% higher in Urban Land Occupation to 1017% higher in Ionising Radiation. The carbon footprint of water produced from the decentralized system was found to be 3.99 kg CO_2-eq/m^3, 809% higher than that from centralized supply. It might be counterintuitive to note that water produced from the RHW POU system could result in higher impacts in Freshwater Ecotoxicity (185% higher), Agricultural Land Occupation (369% higher) and Water Depletion (234% higher). The largest contributor to the overall impacts is the operational electricity use and/or its upstream processes for water produced from the POU device with current UK grid electricity. For example, hard coal mining, electricity production from biogas, and hydropower generation are the dominant unit processes that contributed most to Freshwater Ecotoxicity, Agricultural Land Occupation and Water Depletion, respectively. The shares of the operational electricity use and its upstream processes in the total life cycle impacts range from 59% for Metal Depletion to 99% for Ionising Radiation with 96% for carbon footprint.

Changing the source of the electricity used by the POU device therefore can have a significant effect on the life cycle impacts. If the electricity is supplied by onshore wind, water from this decentralized system would reduce impacts in 11 impact categories including carbon footprint. The other 7 impacts that are increased even with onshore wind power such as the toxicity impacts and Metal Depletion are primarily caused by significantly increased metal use (hence metal mining) in wind power systems compared with the current fossil fuel dominated grid mix. If the electricity is supplied by rooftop solar PV, which is the most popular and practical domestic renewable electricity generation technology in the UK, water from the decentralized system would increase impacts in 16 out of the 18 impact categories, including a carbon footprint that is 76% higher than water from centralized supply.

Under the 2030 grid mix scenario, impacts in 10 impact categories are reduced for water from the decentralized system compared with the current grid mix scenario. However, impacts in the other 8 impact categories increased, primarily due to increased use of low carbon energy technologies such as renewables and nuclear. Similar patterns were apparent for water from centralized supply as electricity use is also a significant contributor to most impacts (e.g., 27% of carbon footprint for centralized water under the current grid mix scenario). Overall, water from the decentralized system still results in increased impacts in all 18 impact categories compared with that from centralized supply under the 2030 grid mix scenario.

As there are no other LCA studies on potable water produced from RHW, it was not possible to directly compare our results with similar studies. However, life cycle fossil fuel consumption of bottled water (5600–10,200 MJ/m^3) (Gleick and Cooley, 2009) was found to be two orders of magnitude higher than that of water produced from the RHW POU system tested in this study (1.179 kg oil-eq or 49.4 MJ/m^3). Similarly, the carbon footprint of bottled water (71.1–317.8 with a mean value of 162.4 kg CO_2-eq/m^3reported in Fantin et al. (2014) or 150 kg CO_2/m^3 mentioned earlier) was also found to be two orders of magnitude higher than that of water produced from the RHW POU system (3.99 kg CO_2-eq/m^3). In addition, life cycle fossil fuel use and carbon footprint of potable water produced from the RHW POU system are much higher than those of water produced from RHW for non-potable use (Ghimire et al., 2014; Morales-Pinzón et al., 2012), primarily because of the increased energy used for treating and maintaining the water to potable standard.

Table 2
Summary of water saving efficiency during 2015 for the Exeter RWH POU system.

Month	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
ET (%)	26.7	58.7	0.6	95.5	27.0	20.4	31.6	62.0	23.9	67.3

Table 3
Life cycle impact assessment results for 1 m^3 of potable water from centralized supply and the decentralized RHW POU system under different electricity supply scenarios.

Water supply		Centralized	RHW POU			Centralized	RHW POU
Electricity source (UK)		Current gird mix	Current grid mix	Onshore wind	Rooftop solar PV	2030 grid mix	2030 grid mix
Impact category	Unit						
Climate change	kg CO_2 eq	0.4388	3.9901	0.2573	0.7735	0.2504	1.4663
Ozone depletion	kg CFC-11 eq	0.00000002	0.00000023	0.00000003	0.00000014	0.00000002	0.00000028
Terrestrial acidification	kg SO_2 eq	0.0019	0.0169	0.0015	0.0053	0.0012	0.0069
Freshwater eutrophication	kg P eq	0.00012	0.00131	0.00027	0.00077	0.00007	0.00061
Marine eutrophication	kg N eq	0.00008	0.00075	0.00010	0.00034	0.00006	0.00051
Human toxicity	kg 1,4-DB eq	0.1459	1.3699	0.5012	1.4318	0.1191	1.0110
Photochemical oxidant formation	kg NMVOC	0.0012	0.0084	0.0011	0.0032	0.0009	0.0039
Particulate matter formation	kg PM_{10} eq	0.0007	0.0050	0.0006	0.0020	0.0005	0.0022
Terrestrial ecotoxicity	kg 1,4-DB eq	0.0001	0.0011	0.0000	0.0011	0.0001	0.0013
Freshwater ecotoxicity	kg 1,4-DB eq	0.0111	0.0315	0.0483	0.1532	0.0118	0.0419
Marine ecotoxicity	kg 1,4-DB eq	0.0087	0.0332	0.0429	0.1373	0.0092	0.0400
Ionising radiation	kBq U235 eq	0.1008	1.1258	0.0199	0.1035	0.1509	1.7971
Agricultural land occupation	m^2a	0.0257	0.1205	0.0174	0.0509	0.0330	0.2174
Urban land occupation	m^2a	0.0168	0.0269	0.0101	0.0099	0.0166	0.0246
Natural land transformation	m^2	0.0001	0.0008	0.0000	0.0001	0.0001	0.0004
Water depletion	m^3	1.7635	5.8964	0.8278	9.9977	2.5675	16.6661
Metal depletion	kg Fe eq	0.0255	0.1835	0.1445	0.3049	0.0271	0.2058
Fossil depletion	kg oil eq	0.1159	1.1790	0.0700	0.2008	0.0617	0.4530

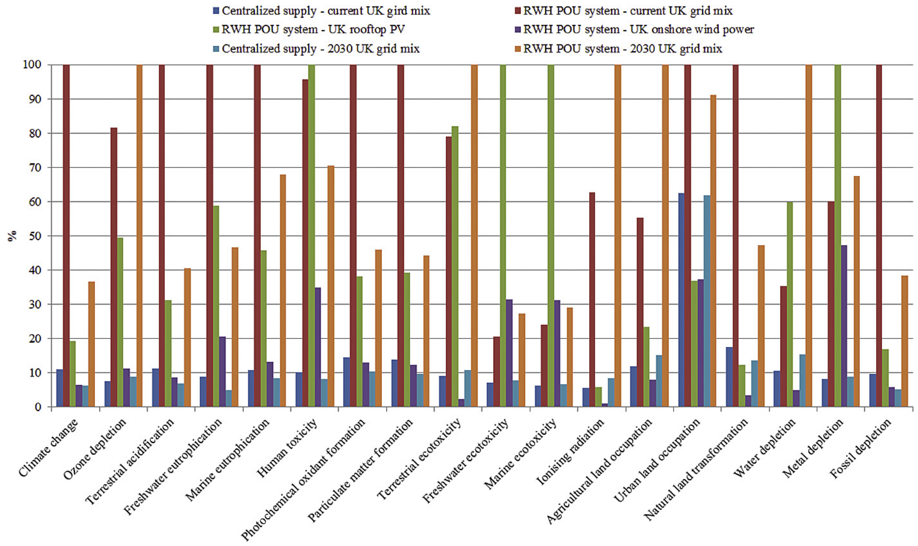

Fig. 4. Relative LCIA results for 1 m^3 of potable water from centralized supply and the decentralized RHW POU system under different electricity supply scenarios (the option with the highest impact in each category is shown as 100%).

3.3. *Limitations*

The results from this LCA need to be interpreted with caution as the currently available LCA methodology and software tools have significant limitations. For example, LCA studies using SimaPro software and ecoinvent database are static and not spatially explicit. Impacts of water systems can vary significantly due to geographical, temporal and operational differences, which cannot be taken into account with existing LCA methodologies and tools. Some of the environmental and social benefits of RHW POU systems cannot be captured by existing LCA methodology, including, for example, the potential for flood mitigation and enhancing water security.

Because of the difficulty in obtaining data, the study did not compare the broader use of RHW POU systems within the overall water delivery process, for example where the delivery of water to a remote location would involve either the installation of significant pipework, the joining to a group water scheme or the sinking of an individual well for a site. It also did not consider a situation where multiple RHW POU systems could be used as an alternative to a new municipal site.

The POU device at the University of Exeter test site only supplied water for toilet flushing. However, the water produced was potable quality and therefore could potentially be used for other purposes such as drinking and washing in the building where it was installed. Further research is needed to assess the overall impacts when other uses are also considered. In addition, this LCA can only considered preliminary as the POU device on which it is based is still a prototype. Future improvements could result in significant energy efficiency increases with much reduced electricity use and hence impacts associated with electricity provision.

4. Conclusions

In this paper, we present an overview of the performance of a novel POU treatment device used to treat harvested rainwater to potable standard. The field trial shows that the POU device was able to deal with the scale of roof runoff supply originating from a RWH system at a commercial building scale and produce water of potable quality. Our LCA based on data collected from the trial suggests that potable water produced from the decentralized RWH POU system currently performs more poorly than that from centralized supply from an environmental perspective. This is to be expected because of the large differences in the magnitude of throughput between a city-scale water treatment unit and a single POU treatment device. The key contributor for impacts of the decentralized RWH POU system was found to be the electricity consumption during the operation stage, in agreement with earlier studies. Its impacts in most categories would be significantly reduced if the electricity were supplied from a renewable source such as solar PV or wind turbines instead of the UK grid. Therefore, to improve the design of decentralized RWH POU systems for potable water production from an environmental perspective, priority should be given to optimizing the energy efficiency of the POU treatment device and exploring opportunities for combined use with renewable energy technologies.

If the hybridization of water systems to include complementary centralized and decentralized systems is to gather momentum to address issues of water security, future work should further explore the wider impacts of RWH POU systems in different localities using emerging spatiotemporal LCA methods (such as that of Maier et al., 2017). This will enable a more context-specific assessment of the environmental and social impacts of RWH POU systems taking into account local environmental characteristics, climatic patterns, water demand profiles and existing water infrastructure configurations. More research is also needed to test the RWH POU system for multiple uses such as drinking and washing in addition to toilet flushing. Modelling and/or monitoring of the electricity consumption by the different processes and components of the system will help identify technological options for energy efficiency improvements. All of these will contribute to a more comprehensive understanding of the life cycle sustainability of the RWH POU technology.

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