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Life Cycle Assessment of Domestic and Agricultural Rainwater Harvesting Systems

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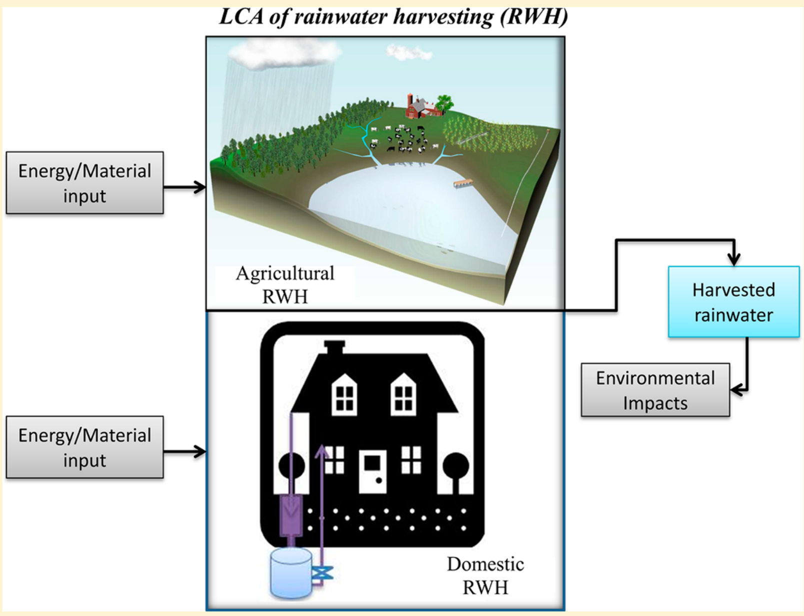
Supporting Information



ABSTRACT: To further understanding of the environmental implications of rainwater harvesting and its water savings potential relative to conventional U.S. water delivery infrastructure, we present a method to perform life cycle assessment of domestic rainwater harvesting (DRWH) and agricultural rainwater harvesting (ARWH) systems. We also summarize the design aspects of DRWH and ARWH systems adapted to the Back Creek watershed, Virginia. The baseline design reveals that the pump and pumping electricity are the main components of DRWH and ARWH impacts. For nonpotable uses, the minimal design of DRWH (with shortened distribution distance and no pump) outperforms municipal drinking water in all environmental impact categories except ecotoxicity. The minimal design of ARWH outperforms well water in all impact categories. In terms of watershed sustainability, the two minimal designs reduced environmental impacts, from 58% to 78% energy use and 67% to 88% human health criteria pollutants, as well as avoiding up to 20% blue water (surface/groundwater) losses, compared to municipal drinking water and well water. We address potential environmental and human health impacts of urban and rural RWH systems in the region. The Building for Environmental and Economic Sustainability (BEES) model-based life cycle inventory data were used for this study.

INTRODUCTION

Cities across the U.S. and worldwide face challenges (e.g., stress on water resources availability)[1] from growing populations and anthropogenic impacts such as urbanization, intensification of agriculture, and land development.[2−5] These drivers increase stormwater runoff, energy use, water scarcity,[6] greenhouse gas (GHG) emissions and climate change impacts,[7,1] and affect human and ecosystem health. These challenges require creativity and appropriate data and modeling tools for sustainable water resource management. Stormwater management utilizing green infrastructure (GI)[8] has emerged as a viable approach.[9] Applicable GI methods include rainwater harvesting (RWH), green roofs, planter boxes, rain gardens,

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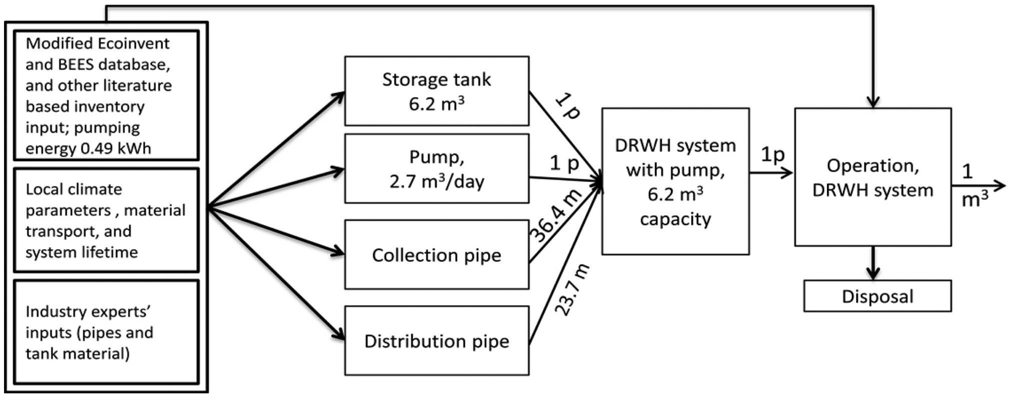

Figure 1. LCA for DRWH system (*p* = piece; BEES = Building for Environmental and Economic Sustainability database).

permeable pavements, and vegetated swales. The practice of RWH is increasing globally,[10−13] and we evaluate RWH as an underutilized method (particularly for agricultural needs) by comparing its environmental impacts to those of municipal drinking water and well water.

In addition to augmenting water supply systems, RWH reduces stormwater runoff, mitigates sewer overflows, decreases watershed pollution, and reduces water demand resulting in energy savings.[14] Harvested rainwater can be utilized for domestic nonpotable toilet flushing and clothes washing, landscape irrigation and agricultural crop irrigation. RWH studies have addressed health improvement,[15] rainwater harvesting strategies,[16] water savings and cost assessment,[17] energy use, carbon emissions, and cost assessment.[18] Others have studied water availability, human health impacts, and freshwater consumption from a life cycle assessment (LCA) perspective.[19,20]

While a number of studies have suggested that RWH may have significant benefits, this study provides a first of its kind full LCA of RWH systems in the U.S. context. Examples include LCA of rainwater for clothes washing and toilet flushing in Switzerland;[21,22] environmental assessment of RWH for clothes washing in Spain;[23−25] energy and carbon implications of RWH in the U.K.;[26] and LCA of water supply technologies including RWH, well fields, and seawater desalination in Denmark.[27] Few studies address RWH environmental impacts of energy use, GHG emissions, global climate change, human health and ecosystem health, and they focus on Europe. The LCA studies of RWH discussed above demonstrate site-specific results, even within Europe. As an example, Crettaz et al. (1999) reported that RWH for toilet flushing was more unfavorable than a conventional water supply but performed better in energy use for a threshold energy demand at 0.8 kWh/m^3.[22] Bronchi et al. (1999) indicated reduced energy consumption and smaller environmental impacts of RWH for clothes washing at a university.[21] Angrill et al. (2012) reported lower environmental impacts of RWH for laundry use in Mediterranean urban areas.[25] Godskesen et al. (2013) found urban RWH designed for a Danish city to be the best alternative with the lowest environmental impact relative to groundwater withdrawal and seawater desalination.[27] A life cycle assessment of energy use, carbon emissions, and costs of RWH for high efficiency toilet flushing in a university building (considering only manufacturing and operational phases) indicated RWH was preferable to potable water flushing.[18] This study fills a gap in the peer reviewed literature by providing a comprehensive LCA of domestic and agricultural RWH in the U.S.

Objectives, Scope, and Novel Contribution. Our objective is to evaluate the environmental and human health impacts of domestic and agricultural RWH systems for a representative U.S. watershed. We compare RWH impacts to conventional water supplies of municipal drinking water and well water irrigation using a suite of impact potential metrics including human toxicity (human health and criteria pollutants), ecotoxicity, global warming potential, fossil depletion, metal depletion, ozone depletion, acidification, smog, eutrophication, blue and green water depletion, and cumulative energy demand. The Building for Environmental and Economic Sustainability (BEES)[28] data set provided materials likely to be used in RWH systems.

Our study comprehensively addresses environmental impacts of domestic and agricultural RWH systems for a representative U.S. watershed which, to our knowledge, has not been done. This study contributes to the existing literature on RWH by (i) providing a comprehensive suite of LCA results relevant for decision-making in a U.S. context and (ii) providing a transparent set of publicly available unit processes which can be used to recreate these results and modified to represent other situation-specific considerations. The model is broadly applicable to regions with comparable annual rainfall, landform, crop water demand and household water usage. Our study provides a firm basis for future LCA studies of other RWH system configurations. This is necessary for identifying appropriate ways to integrate RWH elements to improve water resource management and minimize related local and global environmental impacts.

■ MATERIALS AND METHODS

Four water supply options were addressed: domestic RWH or DRWH, agricultural RWH or ARWH, municipal drinking water, and crop irrigation using well water. We designed baseline systems for rainwater collection, storage, and delivery, as well as energy and infrastructure necessary for urban and agricultural uses. "Baseline design" refers to starting points for DRWH and ARWH systems and "minimal design" refers to a near-optimal design with minimal infrastructure and energy use. We performed a screening-level LCA of potential pipe materials, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), cast iron, and two potential tank materials, concrete and polyethylene (PE).

We consulted the National Association of Home Builders and Plastic Pipe and Fittings Association regarding appropriate

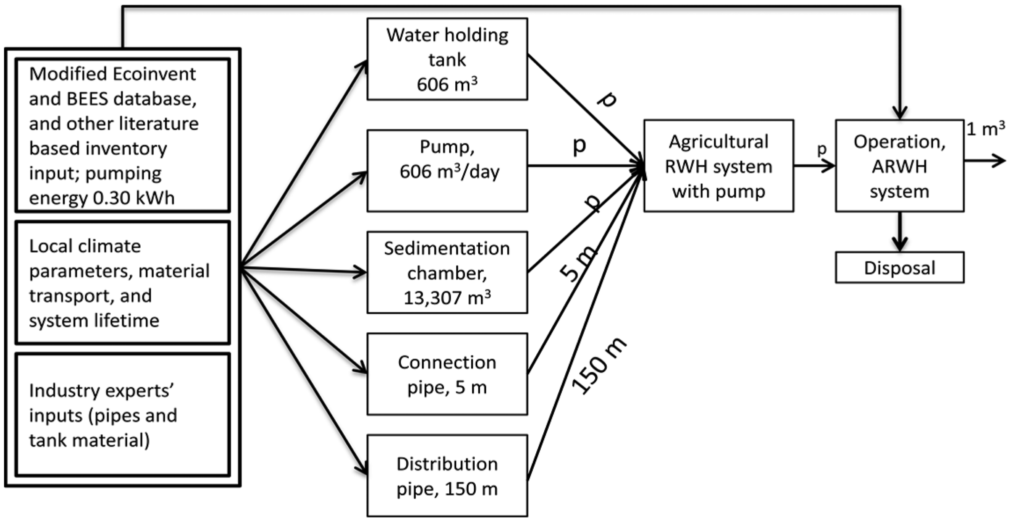

Figure 2. LCA for ARWH system (p = piece; BEES = Building for Environmental and Economic Sustainability database).

infrastructure for the DRWH system and life cycle inventory (LCI) data. We selected PVC pipe for outdoor use and CPVC pipe for indoor use for the DRWH system. PVC pipe was also selected for the ARWH system and PE storage tanks were selected for both.

The DRWH system included rainwater collected from the rooftop of a single-family residential home, tank storage, and distribution for nonpotable use in toilet flushing. The ARWH system included rainwater collected from the upland catchment of a family farm into a sedimentation chamber, impoundment storage, and irrigation of pasture/hay and crops. We compared environmental impacts of DRWH and ARWH systems to municipal drinking water and well water. The LCA procedure followed the International Organization for Standardization's LCA standards, as well as other guidance in the field.[29−32]

We modeled the DRWH and ARWH systems from cradle-to-grave (i.e., raw material acquisition, manufacturing, use/maintenance to disposal) for comparison to their counterpart water supply options, municipal drinking water and well water. Source water treatments apply to municipal drinking water only. Water storage, distribution to the point-of-use, end-of-life disposals, and transportation of materials at each stage were included within the boundary. Electricity use, medium and low voltage at grid (U.S.), was included within the boundary.

The LCA system boundary for the analyzed four options is described in the Supporting Information (SI). Figures 1 and 2 depict the LCA diagrams of the DRWH and ARWH systems.

Functional Unit. The functional unit was 1 m^3 water for both nonpotable domestic use and agricultural irrigation. Using a standard unit facilitates comparison of municipal drinking water and well water to rainwater. The functional unit accounted for annual water demand and system service life. In order to compare systems that supply adequate volumes on-demand to meet household and crop irrigation needs, DRWH and ARWH systems were designed to provide 0.102 m^3 day^{-1} and 606 m^3 day^{-1}, respectively. See the SI for the assumptions and calculations underlying these estimates.

Study Location. The Back Creek watershed within the Albemarle-Pamlico river basins in Virginia and North Carolina was selected for this study, building upon previous work.[33,34] Back Creek is 152 km^2 with a rural population density of 101 persons/km^2. Demographic and geographic information, a watershed map, and additional details are found in the SI.

Domestic Rainwater Harvesting System. Components of the DRWH system included a storage tank, pump, pipes, gutter, filter, and valves. The storage design volume of 6.2 m^3 was based on toilet water requirements with two months capacity for a typical household in the watershed. The DRWH system was designed to provide nonpotable water for toilet flushing only. The average daily demand for a low-flush toilet was 37.8 L per capita per day (pcpd).[35] To estimate length of gutter and down pipe, we used a 16 m long by 14 m wide by 6.4 m high two-story house with average roof area of 220 m^2.[36] A cylindrical PE tank was buried outside a corner of the house (Figure 3). A submersible 0.5 hp steel pump at the base of the

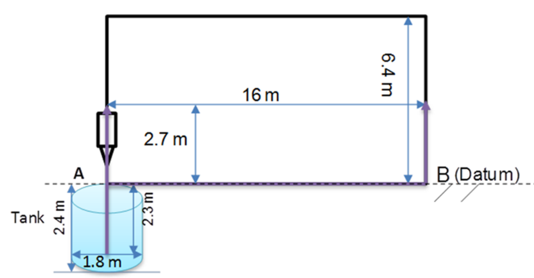

Figure 3. Schematic of DRWH system (side view).

tank provided system pressure for toilet flushing. The LCI for a PE tank was based on a 25.4 mm-diameter water supply PE pipe from the BEES database.[28] From BEES we also selected data on 19 mm ($^3/_4$-in) CPVC distribution pipe and 101.6 mm (4-in) PVC collection pipe.[37] Transportation flow data of pipe and tank material from factory to site was included. A distance of 322 km was used for shipping the product from a manufacturing plant in Charlotte, North Carolina to a site in Roanoke, Virginia.

For the DRWH system we also evaluated reducing pipe length and eliminating the pump (minimal DRWH design). Pipe length was reduced from 23.7 to 5 m by locating the storage tank and toilets on the same side of the house (Figure 3). Note that elimination of the pump required locating the storage tank above the level of a toilet which necessitated including structural reinforcement steel to withstand the weight

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of maximum storage capacity. Existing gutter and downspouts were utilized.

A 6-mm mesh screen in the collection system filtered leaves and a filter sock of nylon mesh installed on the pipe at the tank prevented coarse particulate matter from entering the storage tank.[38] Chemical treatment, cross-contamination, and potential exposure[39] were beyond the scope of this study. Regulations governing rainwater use vary by municipality and should be consulted.

Agricultural Rainwater Harvesting System. The ARWH system consisted of catchment, channel, sedimentation chamber (storage pond), water-holding tank, pump, irrigation equipment, pipes, valves, and filter (Figure 4). The catchment

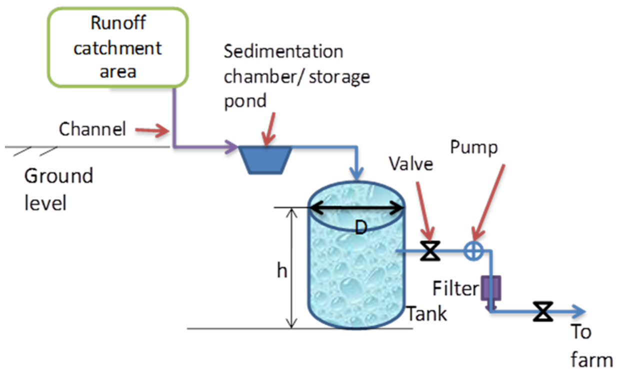

Figure 4. Schematic of ARWH system (not to scale).

included forest, pasture and other land uses. In many drought-prone regions, catchment surface treatments such as water-proofing by compact soil, melted wax, or plastic films are used[40] but were not included here. The sedimentation chamber also functioned as the storage pond. The water-holding tank size was based on average daily water needs for supplemental irrigation of a corn crop for the year 2001 in the southeastern U.S.[41,42] Salazar et al. reported year 2001 as a normal year based on the 50th percentile distribution of irrigation demand in the region.[41] Irrigation volume for a 0.34 km^2 farm with 80% irrigation efficiency (ratio of the average depth of beneficially irrigated water to the depth applied)[42] was estimated to be 606 m^3/day.[43] We designed the sedimentation chamber with an annual runoff volume of 13 000 m^3, based on principles of a stormwater filtering system design sufficient for a 25.4 mm rainfall event.[44] A pump with the total dynamic head of 70 m met the supplemental irrigational demand[45] which is based on average supplemental irrigation of a corn crop in a normal year, 2001. Energy use for irrigation was 0.3 kWh/m^3.[46] A 5 m-long 101.6 mm-diameter PVC pipe with a density of 3 kg/m connected the sedimentation chamber to a PE water-holding tank with capacity of 606 m^3. A 150 m-long 101.6 mm PVC pipe distributed water from the tank to surface irrigation equipment.[47] Irrigation equipment material inventory was obtained from the Ecoinvent version 2.2 database.[47] The minimal ARWH system eliminated the pump. Chemical treatment or transport and fate of fertilizer and pesticide runoff in rainwater were beyond the scope of this study.

It is worth noting that each watershed, household, and farm may have different water demands and availability that impact the design of RWH systems. For example, a system with high demand from a household would require a comparatively large storage tank. In that case, productivity of the tank (i.e., yearly water production in m^3 /volume of tank in m^3) is important. Productivity of domestic RWH and agricultural RWH tanks were 6 (37 m^3/6.2 m^3) and 150 (90 854 m^3/606 m^3). This factor influences LCIs of the tank infrastructures and affects environmental performance of the system.

Additional details on both systems are available from the SI. Assuming very small impact, valves and filters were not included in the LCA. A background analysis for this was conducted and is presented in SI. The following assumptions were made:

i. DRWH and ARWH systems have a 50-year service life (see Table 1).
ii. Pumps were replaced at the end of their service life, i.e., 15 years.

Table 1. Domestic and Agricultural RWH System Characteristics

Component	description	dimension	service life (year)[25,37,49,51]	LCI data source[28,49]
DRWH				
storage	tank, polyethylene	6.2 m^3	50	NIST (2013)
collection	gutter, half-open 101.6 mm-diameter (dia.) 60 m PVC, equivalent to 30 m solid PVC	30 m	50	NIST (2013)
collection	down pipe, 101.6 mm-diameter PVC	6.4 m	50	NIST (2013)
distribution	pipe, 19 mm-diameter CPVC	23.7 m	50	NIST (2013)
pump	1 unit	2.7 m^3/day	15	Ecoinvent (2012)
electricity, pumping to the point of use	electricity, medium voltage, at grid (U.S.)	0.49 kWh	not applicable	Ecoinvent (2012)
ARWH				
storage	tank, polyethylene	606 m^3	50	NIST (2013)
collection	pipe, 101.6 mm-diameter PVC	5 m	50	NIST (2013)
distribution	pipe, 101.6 mm-diameter PVC	150 m	50	NIST (2013)
pump	1 unit	606 m^3/day	15	Ecoinvent (2012)
electricity, pumping to the point of use	electricity, medium voltage, at grid (U.S.)	0.3 kWh	not applicable	Ecoinvent (2012)
digger	1 unit (sediment dredging for maintenance)	Piece	10 000-h	Ecoinvent (2012)

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Table 2. LCIA Values of the Minimal DRWH and ARWH Systems, Municipal Drinking Water, And Well Water: Reported Per Functional Unit, i.e., per m^3 Water Delivery (CTU = Comparative Toxic Units)

Impacts	unit	minimal DRWH	municipal drinking water	minimal ARWH	well water
Global					
energy demand	MJ	5.8×10^{00}	1.4×10^{01}	1.6×10^{00}	7.0×10^{00}
fossil depletion	kg oil eq	1.3×10^{-01}	2.3×10^{-01}	2.8×10^{-02}	1.3×10^{-01}
global warming	kg CO_2 eq	4.1×10^{-01}	8.5×10^{-01}	8.4×10^{-02}	3.4×10^{-01}
metal depletion	kg Fe eq	3.1×10^{-02}	3.5×10^{-02}	5.2×10^{-02}	6.5×10^{-02}
ozone depletion	kg CFC11 eq	8.8×10^{-09}	4.8×10^{-08}	6.7×10^{-09}	2.0×10^{-08}
Regional					
Acidification	kg SO_2 eq	6.4×10^{-04}	6.4×10^{-03}	2.6×10^{-04}	2.0×10^{-03}
Smog	kg O_3 eq	1.8×10^{-02}	4.7×10^{-02}	4.5×10^{-03}	2.2×10^{-02}
Local					
green water use	m^3	1.0×10^{00}	0.0×10^{00}	1.0×10^{00}	0.0×10^{00}
blue water use	m^3	1.0×10^{-03}	1.2×10^{00}	5.9×10^{-04}	1.0×10^{00}
ecotoxicity, total	CTU	7.3×10^{-04}	6.3×10^{-04}	3.1×10^{-04}	1.1×10^{-03}
eutrophication, total	kg N eq	4.0×10^{-04}	4.1×10^{-03}	2.9×10^{-04}	1.2×10^{-03}
human health criteria	kg $PM_{2.5}$ eq	5.3×10^{-05}	4.4×10^{-04}	6.2×10^{-05}	1.9×10^{-04}
human health, cancer, total	CTU	2.5×10^{-11}	2.9×10^{-11}	6.6×10^{-12}	1.6×10^{-11}
human health, noncancer, total	CTU	9.2×10^{-12}	6.0×10^{-11}	2.4×10^{-11}	6.5×10^{-11}

Municipal Drinking Water and Well Water. The municipal drinking water LCA boundary includes source water acquisition, predisinfection (conditioning with GAC adsorption), primary and secondary disinfection (gaseous chlorine and sodium hypochlorite), storage, water works, pump station, distribution, that is, pumping energy for treated water transportation, sodium hypochlorite and fluoridation, and water networks.[48,49]

The LCA system boundary of well water irrigation includes raw material extraction through disposal of irrigation system components, including irrigation equipments, excavation, piping, shed, and a tractor for a typical U.S. irrigating system. Applicable transportation requirements of the stages (e.g., water acquisition and disposal) and pumping energy for water acquisition and distribution were included in both municipal drinking water and well water systems.

Life Cycle Inventory Data. The LCI of CPVC for distribution, PVC for collection, and PE for tank materials were obtained from the BEES online model.[28] LCIs for pumps, pumping electricity, cast iron pipe, concrete tank, material transportation, and material disposal were obtained from the Ecoinvent database version 2.2.[49] The minimal design inventory was determined by reducing pipe to 5 m CPVC for DRWH and eliminating pumps for DRWH and ARWH systems. LCI data for municipal drinking water and well water irrigation were obtained from the U.S. Environmental Protection Agency (EPA),[48] Ecoinvent version 2.2 database,[49] Althaus et al.[50] and Nemecek et al.[47] The LCI of municipal drinking water was developed using a database of a midwestern U.S. drinking water treatment facility developed by the U.S. EPA[48] and the Ecoinvent version 2.2 database for the pipe network, water storage, and pump station. The life cycle inventory of well water irrigation was adapted from Ecoinvent version 2.2. System components and associated information are listed in Table 1, with more information on inventory development in SI. LCI inventory for well and municipal drinking water are in the SI.

Modeling and Impact Estimation. Publicly available software OpenLCA was used for all calculations.[52] The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.0[53] life cycle impact assessment (LCIA) method was used, along with blue and green water use adapted from water footprint methods.[54] Blue water use is consumption of surface and groundwater resources versus green water as captured rainwater.[54] Fossil and metal depletion methods are based on the ReCiPe method[55] and the nonrenewable cumulative energy demand is based on the method provided with the SimaPro software package for use with Ecoinvent version 2.2.[56] TRACI 2.0 methods for characterization included human toxicity and ecotoxicity adapted from the USETox model[57] and were adjusted by removing characterization of metal toxicity due to its uncertainty.[53,58,59] Details on the TRACI method are available elsewhere.[60] LCIA results were analyzed for percentage contribution of RWH system components to identify the most important components. Results were then normalized to maximum impact for DRWH and ARWH systems. We compared LCIA results of baseline and minimal designs of DRWH and ARWH systems to conventional water supply options of municipal drinking water and well water.

■ RESULTS AND DISCUSSION

Both DRWH and ARWH systems have potential to reduce municipal and well water use.[61] From a life cycle perspective, the DRWH system also provided an additional 20% water savings (1.2 m^3 blue water consumption per 1 m^3 municipal drinking water supply) due to inefficiencies (leaks, water use, etc.) in municipal water systems. The life cycle blue water use for both systems was negligible—less than 0.001 m^3 (1 L) blue water per 1 m^3 of green water provided (Table 2). In other words, the water footprint[54] (life cycle blue water use) of supplying 1 m^3 of water through RWH is negligible. The blue water use life cycle impact is closely related to water scarcity which, in water-stressed regions, not only jeopardizes agricultural production but also impacts human health and biodiversity.[62]

This study sheds light on potential environmental impacts when DRWH and ARWH systems are used. Percentage contributions of environmental impacts are categorized as global impacts, regional impacts and local impacts.[32] Energy demand, fossil depletion, global warming potential, metal depletion, and ozone depletion are global impacts. Acidification and smog are regional impacts. Blue water use, ecotoxicity, eutrophication, and human health are local impacts (Figure 5).

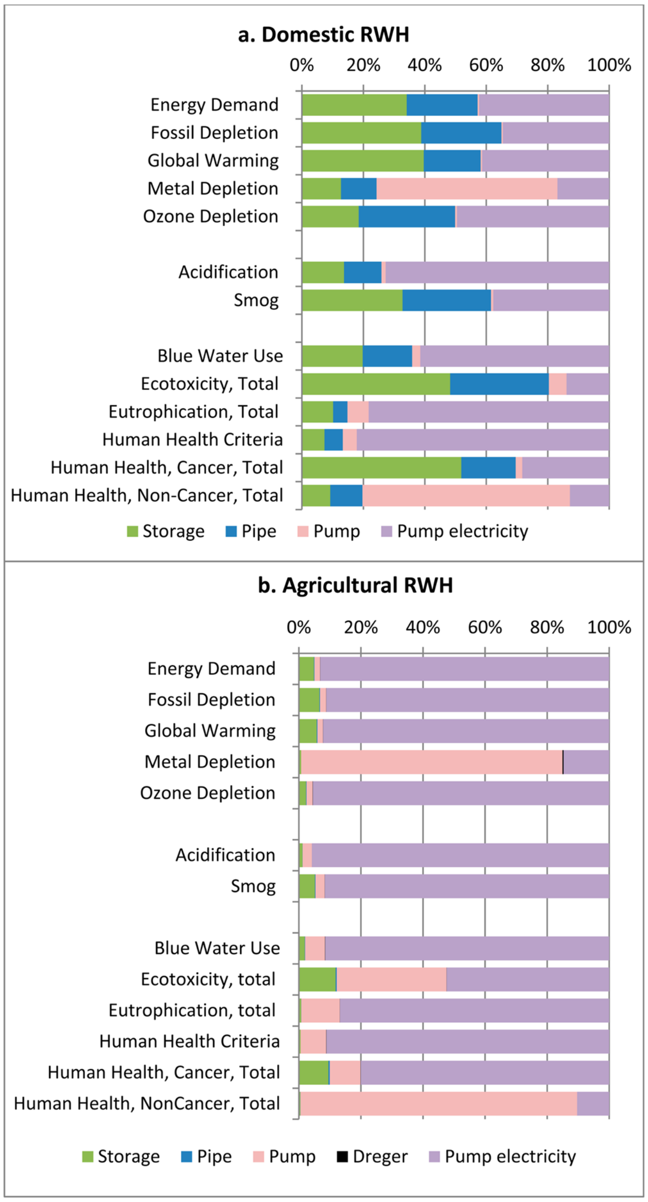

Figure 5. Percentage comparison of LCIA of (a) DRWH and (b) ARWH systems.

The categories reflect the scale of impacts, regardless of release origin. Pump infrastructure and pumping energy were found to be the dominant component in all impacts of ARWH system. For DRWH system, pump and pumping energy were dominant in seven impacts (human health criteria, human health, noncancer, eutrophication, metal depletion, blue water use, and acidification), but the PE tank, PVC and CPVC pipes were also influential in impacts including ecotoxicity, global warming, human health, cancer, energy demand, smog, and fossil depletion (Figure 5). The baseline DRWH performed worse than conventional municipal drinking water in seven impacts (energy demand, fossil depletion, global warming, smog, ecotoxicity, human health cancer and non cancer) of 14 impact categories (Figure 6). The baseline ARWH system out-

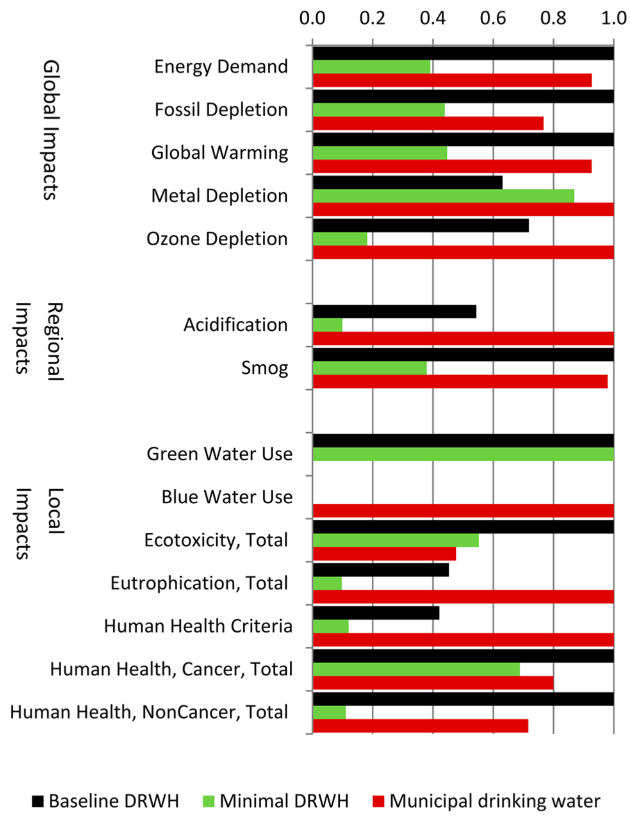

Figure 6. Normalized LCIA of DRWH and municipal drinking water; baseline DRWH system: 60.1 m plastic pipe and pump; minimal DRWH: reduced pipe, 5 m CPVC, and no pump.

performed well water in all impact categories except metal depletion, eutrophication, and human health (noncancer) impacts (Figure 7). Additional information on impacts such as release contributors of the dominating components (pump and pumping energy) of DRWH and ARWH systems to select impact categories as well as contribution analysis for the conventional systems (municipal drinking water and well water) are found in the SI.

With no pump and reduced pipe length, the minimal DRWH design outperformed municipal drinking water in all impact categories except ecotoxicity (Figure 6). The component most responsible for poor performance in ecotoxicity impact was the PE storage tank: 87.4% contribution in ecotoxicity of the minimal DRWH design.

The minimal ARWH design outperformed well water in all impact categories (Figure 7).

The detailed numerical values of LCIA of the minimal DRWH and ARWH systems, conventional municipal drinking water, and well water are reported in Table 2. The DRWH system performed better than municipal drinking water for energy demand (58%), fossil depletion (43%), global warming (52%), metal depletion (13%), ozone depletion (82%), acidification (90%), smog (61%), blue water use (99.9%), eutrophication (90%), human health-cancer (14%) and non-cancer (85%), and human health criteria air pollutants (88%) impacts. The ARWH system performed better than well water irrigation for energy demand (78%), fossil depletion (78%),

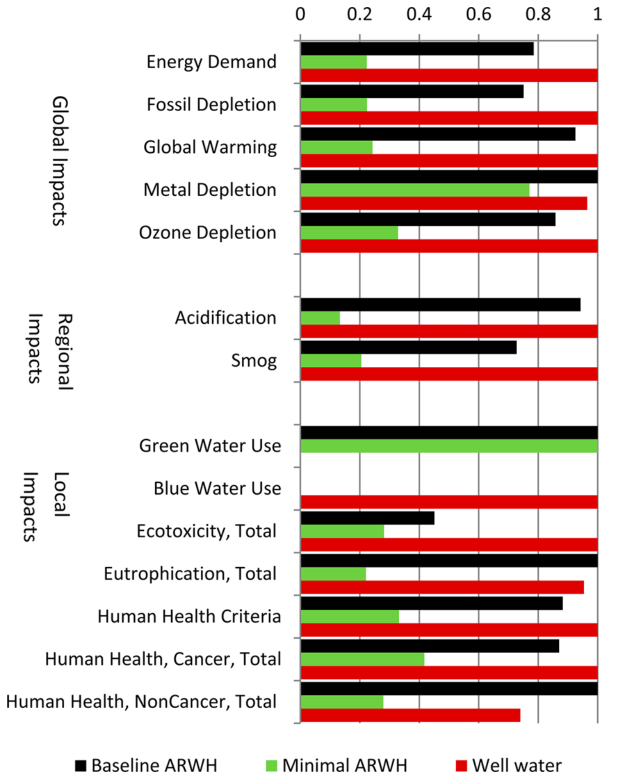

Figure 7. Normalized LCIA of ARWH and well water: Minimal ARWH excludes pump and pumping energy.

global warming (76%), metal depletion (20%), ozone depletion (67%), acidification (87%), smog (80%), blue water use (99.9%), ecotoxicity (72%), eutrophication (77%), human health-cancer (58%) and noncancer (62%), and human health criteria air pollutants (67%) impacts. The reduced impacts of the minimal design RWH systems relative to those of the baseline RWH demonstrate the importance of designing RWH systems to minimize associated collection and distribution infrastructure and energy requirements.

The importance of these releases and associated impact categories should be addressed in planning, especially with increasing adoption of RWH. Reducing these environmental impacts is important not only to human health but also to biodiversity. Knowledge of life cycle impacts associated with RWH systems improves decisions about implementing RWH, including selection of material and sizing and location of system components, and can lead to more sustainable implementation of RWH. RWH has the potential to mitigate impacts of climate and land use change on watersheds by reducing the stress caused by withdrawals from surface water resources and aquifers and subsequently limiting or eliminating the use of chemicals and energy and the delivery of water that is overly treated for nonpotable purposes. Water provision is a critical issue in drinking, irrigation, and aquatic life needs. Exploration of alternative water resources such as RWH is inevitable for water resource sustainability, and this study contributes to future research by focusing on such potential.

If watersheds have different demographics and water demands, these must be accounted for. Higher water demand influences system design, particularly size of storage tank, which leads to higher throughput of process flows, causing increased environmental impacts. RWH adoption rates within a watershed also affect downstream water availability. For example, lower RWH adoption rate (25%) reduced water availability by 6% in contrast to higher RWH adoption rate (100%) in the region, according to a recent study by Ghimire and Johnston.[34]

As this study is watershed-specific, it was not our intention to investigate variations in geographic location, annual rainfall, or water demand. However, the demonstrated methodology is general enough to be applied to watersheds with similar physiographic and climatic properties so long as geography and technology-appropriate life cycle inventory data for RWH, municipal and well water infrastructure and energy sources are available. Please see SI for further information.

To further understand watershed-specific implications of RWH systems, the impact of RWH technology adoption on regional water balances also needs attention. Societal perception, regulatory requirements governing water withdrawal permitting and plumbing codes,[34] and regulations on rainwater use all influence RWH system design. These factors affect material types, sizes, and RWH adoptions rates, which ultimately influence the life cycle environmental impacts of a RWH system.

ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

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Author Contributions

The manuscript was written with contributions of all authors. All authors have approved the final version.

Notes

The authors declare no competing financial interest.

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