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Research paper

Environmental life cycle, carbon footprint and comparative economic assessment of rainwater harvesting systems in schools – a South African case study

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Rainwater harvesting (RWH) provides a unique opportunity for water conservation. This research aimed to assess the performance of two types of RWH systems (gravity and pump-driven) at a local public school in replacing non-potable water for toilet flushing. The volume of harvested water, efficiency to meet demand, expenses involved and associated environmental burdens were key criteria of performance. Economic considerations included capital costs and return periods, while the environmental aspects encompassed simplified life cycle assessments (LCAs) as well as specific carbon footprints. The gravity-fed system supplied 452.5 kL/annum and covered 31.8% of the demand for flushing water for toilets for the school investigated. The pumped system provided 476.8 kL/annum representing 33.5% of the demand. Together they would be able to supply 65.3% of the demand. The catchment area of these two systems differed and there was no overlap. As expected, the gravity-fed system outperformed the pumped system, both economically and environmentally, because no energy for pumping was needed. In terms of costs, the difference was small, and the payback periods of both systems were similar. However, environmentally, the LCA scores for the pumped system were an order of magnitude higher for all 18 impact categories considered. Carbon footprints showed that in the construction stage both systems have similar footprints. For the operation stage, the comparison was extended, as there were higher energy requirements for the pumped system (about 4 times higher than those from the provision of municipal potable water), but in the same range or lower when compared with other alternative sources of water like groundwater abstraction, recycling of municipal water and desalination. The gravity-fed system required no energy for pumping. This study shows how trade-offs in assessing the overall performance of RWH systems can be considered, leading to better decision making.

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INTRODUCTION

Water is an essential resource needed in the domestic, industrial, and agricultural sectors. However, global water depletion and scarcity have become prevalent due to human activities. Many countries already face water-scarcity challenges (Morales-Pinzón et al., 2012), with South Africa (SA) also falling into that category (Cole et al., 2018; Donnenfeld et al., 2018). Thus, water conservation practices like rainwater harvesting (RWH) are important in the local context. RWH is an ancient practice and an effective way of obtaining water for nearby usage (Rahman, 2017; Torres et al., 2020). Recently, it has become a water conservation strategy to deal with the municipal water demands/strains from population growth, urbanization, and climate change (Angrill et al., 2012; Ghimire et al., 2014; Yan et al., 2018; Zabidi et al., 2020). However, water quality issues may limit the use of RWH systems. Potable water uses of harvested rainwater necessitate more intensive treatment (disinfection) and thus, more expense. Therefore, rainwater can more easily (and at potentially lower cost) replace non-potable water activities like toilet flushing, irrigation, car washing, etc. Such systems have been investigated internationally, showing water-saving potentials/efficiencies of 38 to 65% in Italy (Campisano and Lupia, 2017), 27.5 to 60.5% in Brazil (Teston et al., 2018) and up to 80% in Poland (Słyś and Stec, 2020). In South Africa RWH systems have not been assessed in detail environmentally (i.e. there are no LCAs nor carbon footprints published), and with regard to cost estimations research is limited (e.g. Fisher-Jeffes et al., 2017, estimated costs for residential implementation in an area in Cape Town). Hence, this research aims to partially address this gap by providing more details on the environmental and economic performance of these systems.

The economic viability of RWH systems is another important factor, especially in developing countries. While some of the components needed for RWH may already be present in buildings (e.g., roofs and gutters), other parts, like the storage tanks, require financial input. In South Africa some previous RWH schemes have failed due to lack of continuous financial support (Kahinda and Taigbenu, 2011). Besides the economic consideration, environmental impacts also play an increasing role in RWH implementation. In this regard, life cycle assessments (LCAs) and carbon footprints are helpful assessment tools that gauge the environmental impacts of RWH systems throughout their lifespans, i.e., from raw material extraction to construction and processing and, finally, usage and disposal (Ghimire et al., 2017; Yan et al., 2018). These tools can be used in the assessment and optimization of RWH systems, and this process can extend further into design and placement considerations and sizing of tanks (Khan et al., 2017; Marteleira and Niza, 2018). The international literature shows that environmental burdens of rainwater harvesting, as determined by LCAs, depend on specific conditions and the types of systems under consideration. In most cases these systems performed better when compared with centralised water provision systems (see Teston et al., 2022, for a comprehensive review).

However, in some cases, the environmental burdens for rainwater harvesting were higher, in particular when energy consumption associated with increased pumping was necessary (e.g. Anand and Apul, 2011 and Gao et al., 2017).

Schools are in a unique position with regards to the implementation of RWH systems. According to Colvin et al. (2016) and Antunes and Ghisi (2020), RWH systems specifically designed for schools can have an important water-saving potential. Ndiritu et al. (2014) calculated the RWH potential of 32 schools in 3 provinces in South Africa (including KwaZulu-Natal). It was found that rainwater supply could potentially achieve 90% reliability (meaning that the supply would match the demand 90% of the time), that considerable volumes of rainwater can be harvested by existing roofs and that larger storage tanks are needed in schools where summer rain predominates as it coincides with the holidays and a lower demand in schools. When looking at their data, the size of the catchment area (i.e., roofs) was proportional with the number of students and many large schools were included in their analysis. Large schools are of interest for RWH studies as they allow for higher rainwater volumes to be harvested and used within their boundaries, allowing for higher energy efficiency with regard to pumping the harvested rainwater. Vieira et al. (2014) showed that such efficiencies are dependent on high rainwater consumption, which large schools usually have, and which includes non-potable water uses (i.e., toilet flushing, irrigation, general cleaning of windows, floors, etc.); however, such possible efficiencies have not been established locally. Furthermore, Chiu et al. (2009) highlighted that in hilly communities RWH systems can be used as an energy-saving approach in the provision of water, as gravity can replace pumping. In addition, the implementation of RWH in educational settings may instill a water conservation ethos amongst the youth, thereby helping safeguard a valuable resource.

This study aims to identify the RWH potential and assess in detail the economic and environmental performance of RWH systems implemented at a large suburban school in KwaZulu-Natal, SA. The chosen school had to be situated in a hilly area so as to allow for a gravity-fed system, but also had to have an additional flat or low-lying area where pumping is necessary for the transport of harvested rainwater via a different system. For this research, RWH performance referred to how much rainwater could be collected by an appropriate system and then used effectively (also referred to as the water-saving efficiency). Economic considerations include the capital and operational costs of said systems, and environmental criteria refer to such systems' carbon footprints and LCA scores. The inclusion of LCAs allowed for overall detailed assessments of the environmental impacts of RWH systems beyond carbon footprints, by analysing each component material, corresponding transport impacts, and energy impacts from the materials used (construction) as well as from pumping (operation).

CASE STUDY

The case study selected was Duffs Road Primary School located at 2 Robin Road, Durban, KwaZulu-Natal, South Africa. Currently, potable water is provided at the school by the eThekwini Municipality. At the time of the study, 713 learners from Grade R to Grade 7 were enrolled at this school and there were 27 staff members. Therefore, this school is considered a large school as the median number of learners at South African public schools is 412 (Passmark, 2022). A general layout of the school is provided in Fig. 1.

The ablutions block (Block C) was considered for the rainwater supply as it was used by learners from Grades 1 to 7 (633 pupils – representing 85.5% of water user). All roof areas were obtained initially using Google Earth Pro (2021) and checked with measurements on site. Existing components (like the gutters and downpipes) were also incorporated into the RWH design after checking their sizes.

The topography at the school showed a decreasing elevation profile from Block I to Block A (see Fig. 1). This feature is important for gravity-fed RWH systems as no pumping would be necessary to move the rainwater to lower-lying areas. Blocks horizontally adjacent to each other (in reference to Fig. 1) were on the same elevation level. The exception was Block B, which was found to be lower than Block C. As Block B was the largest block, any harvested rainwater from that building would need pumping to Block C. Downpipes were installed at block corners, and therefore tank placement options were limited. A summary of the significant case study characteristics incorporated is shown in Fig. 2.

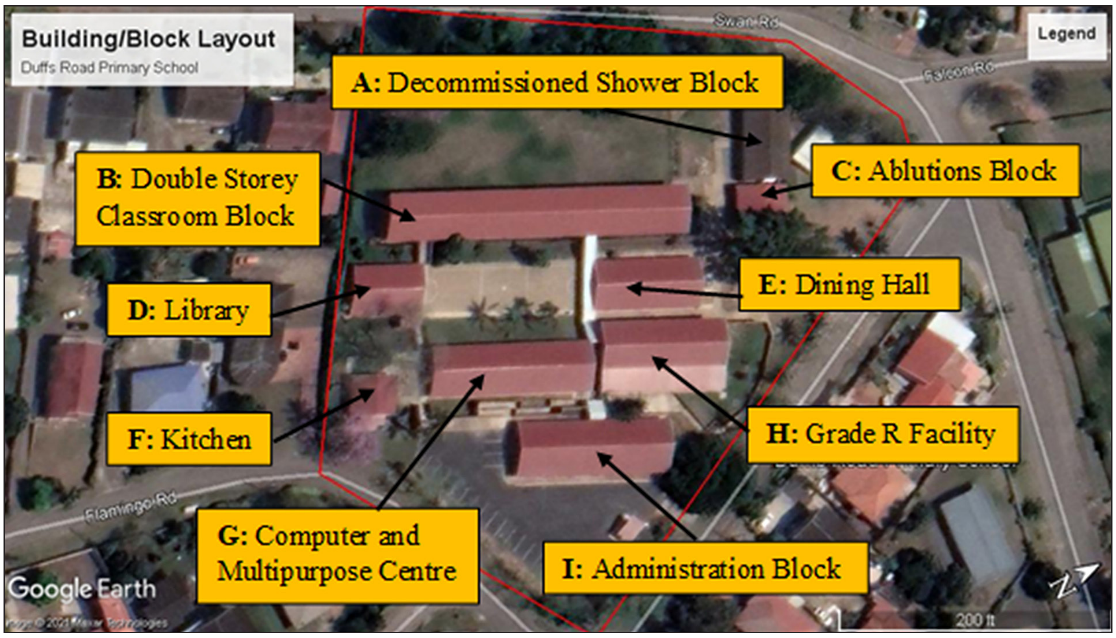

Figure 1. Duffs Road Primary School layout

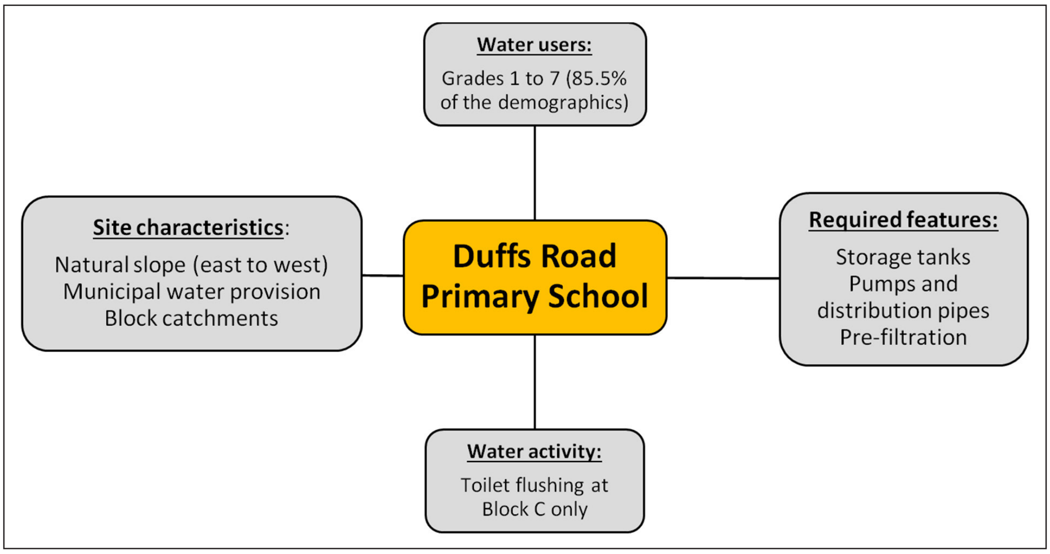

Figure 2. Case study considerations

METHODOLOGY

Two types of RWH systems were investigated: pumped and gravity-fed. For both systems, the target supply block was Block C; however, the roofs providing the rainwater varied. In the pumped system (System 1) rainwater was collected from Blocks A, B, and C (see Fig. 1). These blocks are close to each other, thereby reducing pumping distances. System 2 (gravity-fed) was then designed to harvest rainwater from Blocks E, H, and I (see Fig. 1). These blocks were selected based on the site topography (that would initiate gravity flows) and the proximity to Block C. Attention was paid to ensuring that the catchment areas did not overlap and that both systems had similar catchment sizes.

Case study data collection

The preliminary information required for RWH implementation at Duffs Road Primary included the existing municipal water and energy consumption, historical rainfall data of the area, and the proportion of water used solely for toilet flushing (calculated as 1 424.29 kL/annum). The total water and electricity usage was obtained from the school's municipal bills from 2018, 2019, and 2020. Because of the Covid lockdown and associated school attendance distortions, bills for 2020 were used for comparison only. A questionnaire was administered to the learners using the toilets in Block C to find out how many times each individual uses the toilet when at school. Once this value was established, it was multiplied by the volume of water used for a single flush (measured as 6 Ls) and the number of school days in a given month. School days were assumed according to the sessional dates of public schools. These data were used to calculate the demand for toilet flush water. The values obtained were in the range of 0.3–6.0 L/(learner·day) which is on the lower scale of the international data (0.81–35.43 L/(learner·day) emerging from Brazil (Antunes and Ghisis, 2020). The next important aspect pertained to the potential supply of rainwater; hence, the historical rainfall of the region was obtained. Using the eThekwini Datafeeds website (2021), daily precipitation depths were sourced for the period 2001 to 2020. The closest rain gauge was 4 km away at the 'Newlands Reservoir No.3' station; hence, precipitation data from this station were used.

Implementation and performance

Using the historical rainfall data for the period 2001–2020, weighted averages (based on similar precipitation per month) were calculated, thereby accounting for months with missing data. The weighted averages were then used as the likely rainfall depths (in mm) that would occur at the school for a given month. These were further used to calculate the volumetric rainwater supply by applying Eq. 1:

$$V = R \text{ x } A \text{ x } Cr \tag{1}$$

where: V = harvested rain supply volume (m^3); R = estimated monthly rainfall (mm), A = catchment area (m^2), Cr = runoff coefficient (no units)

A conversion factor of 10^{-3} was applied. The runoff coefficient was taken as 0.9, since the roofs were made up of roof tiles (Worm and van Hattum, 2006). Harvested rainwater volumes were then summed according to catchment areas for each system.

The available supply of rainwater was then compared to the apparent demand (using the toilet flushing survey). In the event that the rainwater amount was less than the monthly consumption, municipal water would be needed in addition to the rainwater harvested. The potential water savings were obtained directly from the estimated volumetric supply scenarios (by using Eq. 1). However, these figures were a preliminary estimate as they were later configured according to the sizes of the standardized tanks used.

The municipal cost savings were calculated through the multiplication of the physical water savings and the water tariff (usage rate) obtained from the eThekwini Municipality. However, cost savings were also based on a fixed charge rate which would only be applied on school days. Equation 2 was used:

$$\text{CS} = \text{WS x UR} + \text{NSD x FR} \tag{2}$$

where:

CS = cost savings (ZAR); WS = water savings (kL); UR = usage rate (ZAR/kL) = 36.52 ZAR/kL; NSD = number of school days; FR = fixed charge rate (ZAR/day) = 56.35 ZAR/day

It should be noted that the usage and fixed charge rates were constant and applied to the water savings and number of school days, respectively.

Carbon footprint calculations were done considering the carbon emissions from construction of both RWH systems, the energy used for pumping in System 1, as well as the carbon savings due to the rainwater replacing potable water (both systems).

According to Friedrich et al. (2009), the processes involved in municipal/centralized water provision also produce carbon emissions due to the abstraction, distribution and treatment of water to achieve potable water quality standards. Hence, rainwater substitution would change these burdens, depending on the amount and type of rainwater harvested and used to replace potable water. The carbon emission factor was taken as 0.4091 kg CO_2 per kL of potable water supplied in the eThekwini Municipality (Friedrich et al., 2009). The water, cost and carbon emissions were calculated for both systems.

Design of RWH system components

The design for the proposed RWH systems involved important components – gutters and downpipes, pre-filtration mechanisms, and storage tanks. Polycop (a type of polyethylene) piping was used for transport from the storage points to the use point (Block C), with pumps present for System 1 only. Regarding the gutter and downpipe design, various checks were performed to verify if the existing gutters and downpipes were sufficient for all the expected rainfall to be collected. It was found that the calculated need for gutters and downpipes was lower than the existing equipment, hence no replacement was necessary. Pumps were selected with standardized features such as 0.37 kW of power, 34 L/min flow rates, brass impellers, stainless steel shafts, cast iron bodies, and automatic operation functions (Jojo, 2021).

The pre-filtration mechanism involved the selection of pre-built, universal components like a first-flush diverter, leaf eater, and tank screen. The first two would be installed along the downpipe allowing for the removal of larger debris. A tank screen would be installed under the lid of every storage tank, acting as a sieve for smaller contaminants. The storage tanks were then selected based on the building catchment volumes/mass balance procedures (see Fernandes et al., 2015, for details) and positioned at appropriate points, i.e., near the downpipes and in unobtrusive locations. This balance approach is that most used in the literature for sizing of tanks for domestic RWH (Semaan et al., 2020). It was noted that all the proposed tank placements were possible according to the platform sizes (100 mm wider than tank diameters), building spans, and downpipe locations. Given that standardized tank sizes were chosen, the water, cost, and carbon savings required slight amendment according to the maximum supply stored by the tanks. These were calculated on a monthly and annual basis.

Economic analysis

The economic analysis for the proposed RWH systems included system capital costs, pump operation costs and the return-on-investment period. Initially, all component prices were sourced from online catalogues, while the installation and maintenance costs were excluded from the analysis as these expenses would not factor into the payback period. The return period for each system was calculated as the ratio of the capital costs to the amended yearly cost savings introduced by the system. The annual pump operation costs (i.e., whenever toilet flushing occurred) were calculated using the daily number of toilet flushes (obtained from the demand survey), scaled up to a monthly and then annual figure based on the number of school days in a month (2019 sessional dates were used as it was the last year before Covid interruptions). The yearly pump operation/usage was equated to the proportioned number of toilet flushes (i.e., the number of flushes consuming the rainwater supply). The yearly pump energy consumption (kWh) was calculated as the product of the pump's motor power (kW) and annual pump operation time (h) needed for the refill of the toilets. The pump operation costs (per annum) were determined using the yearly energy consumption of the pump (kWh) multiplied by the latest energy rate (R/kWh). The annual pump operation costs were compared to the existing energy usage at the school to gauge whether the pump energy contribution was significant. After that, a comparison of the pump costs and system savings was performed.

Environmental analysis

The initial environmental analysis investigated the carbon emission (and global warming) impacts from the component/system materials (embedded carbon), pump carbon emissions, and the period taken to reduce these burdens due to replacing potable water and its associated carbon emissions. By listing each component material and their corresponding masses (in kg), an appropriate carbon emission factor (kg CO_2/kg material) was applied for each material, followed by the addition of all the subsystem carbon emissions resulting in a total carbon footprint for each system. The period to reduce the carbon emission burdens was then estimated as the ratio of the system carbon footprint to the annual carbon emission savings due to this system replacing potable water and the associated carbon footprint. Lastly, the pump carbon emissions were estimated in a similar fashion to the economic costs, by considering the number of toilet flushes per year, the yearly pump operation, cistern refill time, the annual pump operation time, and the pump's energy consumption per year. The carbon footprints of the two systems investigated gave an overall assessment of environmental performance, but no detailed analysis was possible and, therefore, LCAs were undertaken. The carbon emission factors of the RWH components are presented in Table 1.

Table 1. Carbon emission factors of the RWH components

Component	Material	Unit mass (kg)	Carbon emission factor (kg CO_2/kg material)
First-flush diverter	Polyvinyl chloride (PVC)	0.5	2.22
Leaf eater	Polypropylene (PP)	0.7	1.95
Tank screen	Stainless steel	0.1	6.15
Storage tank (10 kL)	Linear low-density polyethylene (LLDPE)	180	1.01
Storage tank (15 kL)	LLDPE	270	1.01
Storage tank (20 kL)	LLDPE	360	1.01
*Platform/base	Concrete	2 400 (per m^3)	0.072
Polycop piping roll 1 (22 mm x 50 m)	PP	5	1.95
Polycop piping roll 2 (22 mm x 25 m)	PP	2	1.95
0.37 kW booster pump (body)	Cast iron	6.75	1.51
0.37 kW booster pump (shaft)	Stainless steel	1.35	6.15
0.37 kW booster pump (impeller)	Brass (copper-zinc alloy)	0.9	6.18
Pump-to-tank connector kit	PP	1.2	1.95

Life cycle assessments

The LCAs for the two systems were computed using the SimaPro tool (Version 9.2.0.2) and the Ecoinvent library databases, which maintained the appropriate standards and guidelines in the LCA context (i.e., ISO 14040 and ISO 14044) (PRé Consultants, 2016). The research was limited to cradle-to-gate analyses and as such simplified LCAs were conducted. The overall scope of the investigation is depicted in Fig. 3. The processes outside the box were not included in the assessment for both systems.

The assembly phase pertained to the production/manufacturing of components requiring retrofitting (i.e., the pre-filtration mechanisms, storage tanks, Polycop piping, pumps, and concrete bases). Thus, existing infrastructure like the gutters and downpipes were not included in the LCAs as their presence is obligatory with or without RWH.

Important foreground data included the material type, unit mass and quantity, as well as lifespan of different components. These were obtained for each RWH system from the respective design. The manufacturing processes for the materials and the energy used for the foreground processes are considered background data and were available from Ecoinvent library databases within the SimaPro tool and were customised for South Africa by using local data for electricity. Since RWH systems functioned towards effective water storage and usage, the functional unit was taken as 1 kL (m^3) of harvested rainwater of non-potable quality to replace potable water for toilet flushing. Because of the non-potable use the difference in the quality of water was deemed as not important and all inputs and outputs were scaled down to this unit of reference.

The **inventory analysis** involved the component foreground data collection from the actual RWH systems designed (primary data). The SimaPro library databases were used to obtain background data, namely, the outputs and inputs from the manufacturing of particular materials used in the design of the RWH systems (secondary data). Component lifespans were taken from the online catalogues used to source the prices. It was important to identify the water volumes over component lifespans to estimate the burdens in terms of the functional unit. Transport distances for materials were researched based on supply warehouse locations, point of purchase, and point of use (i.e., the school).

Finally, the electricity usage over the pump lifespan was estimated as the product of the annual pump energy usage and the pump lifespan. Hence the LCA showed the environmental impacts per component (over their respective lifespans) during the assembly phase (both systems) and operational phase (System 1 only). South African electricity data from the Ecoinvent database were used. All the component masses (kg), transport impacts (tkm), and electricity usage (kWh) were scaled down to the functional unit (1 kL of harvested rainwater).

The LCA **impact assessment** was the next step, and environmental burdens from both systems' construction and operation (including pump energy) for 18 impact categories were modelled according to established methodologies and ISO standards. These impact categories accounted for generalized environmental impacts like global warming, terrestrial acidification, and water consumption, among others. All impact categories were automatically classified since the ReCiPe 2016 Midpoint Hierarchist method was used for the study (Yan et al., 2018).

The **interpretation** of the results was computed using the 'network' and 'analyze' functions on SimaPro. In this tool, the LCI input data were first represented by network diagrams that displayed RWH components as subassemblies of each RWH system. Based on all the materials, electrical, and transport data, environmental scores were calculated for both systems and expressed per kL of harvested rainwater. Together these scores showed the environmental profile of each system in units that allowed comparison. Flow arrows allowed for organizational links between components and their input data to be shown, visualizing the magnitude of environmental burdens for each of the impact categories included.

RESULTS AND DISCUSSION

Implementation and performance

The rainwater supply to be harvested by each system and toilet flushing demand at Block C were calculated using the procedures and equations described in the methodology, and are presented in Fig. 4. October and November had the highest rainfall supply, but this was constrained in terms of storage by the chosen tank capacities. This can be seen in the difference between water volumes available (i.e. collected and stored) for Systems 1 and 2 for these two months.

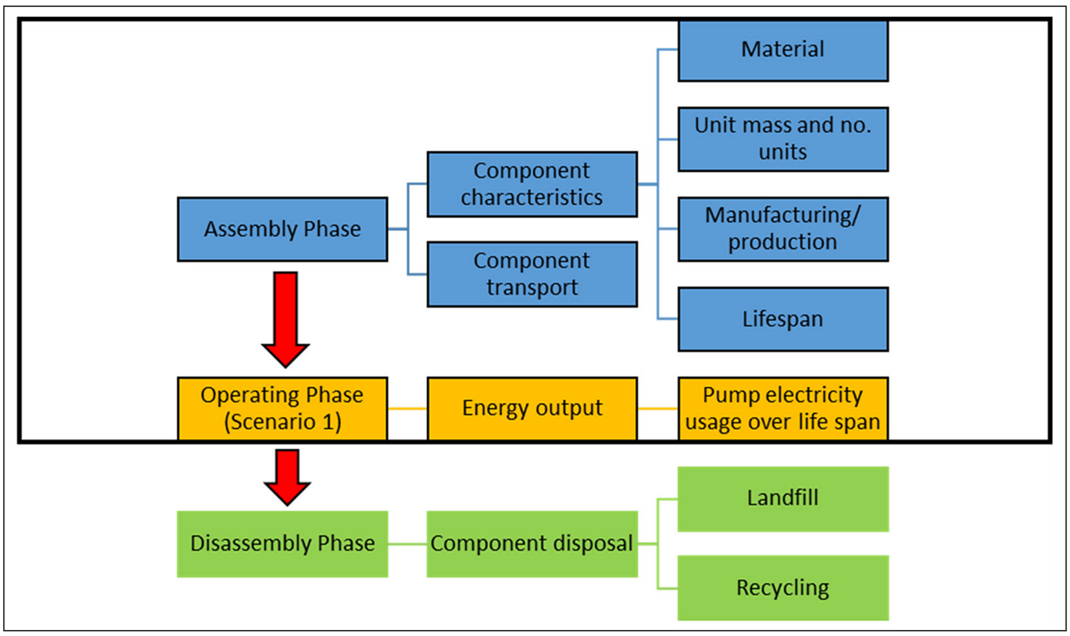

Figure 3. LCA conceptual system boundary and foreground processes

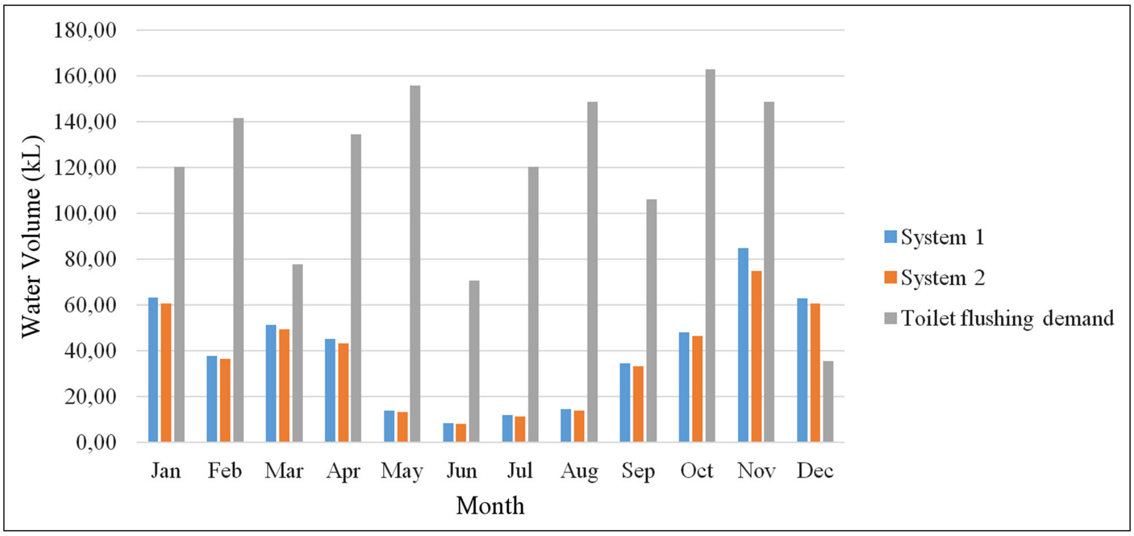

Figure 4. Supply vs. demand (System 1 and 2)

Table 2. Tank characteristics – System 1

Tank capacity (kL)	Diameter (m)	Height (m)	Tank quantity per block	Minimum platform width (m)
15	2.6	3.26	1 x 15 kL tank @ Block A 1 x 15 kL tank @ Block B 1 x 15 kL tank @ Block C	2.7 8.1 2.7
20	2.6	4.27	2 x 20 kL tank @ Block B	8.1

Table 3. Tank characteristics – System 2

Tank capacity (kL)	Diameter (m)	Height (m)	Tank quantity per block	Minimum platform width (m)
10	2.3	2.8	1 x 10 kL tank @ Block H 1 x 10 kL tank @ Block I	5.1 5.1
15	2.6	3.26	1 x 15 kL tank @ Block E	2.7
20	2.6	4.27	1 x 20 kL tank @ Block H 1 x 20 kL tank @ Block I	5.1 5.1

The toilet flushing demand was shown to exceed the available rainwater supply for all months except December, for both systems investigated. December was an exception because of school holidays. Overall, the annual toilet flushing demand amounted to 1 424.29 kL, while the rainwater collection for System 1 was at 476.76 kL/year and that for System 2 at 452.48 kL/annum. Hence, the water-saving efficiency (WSE), taken as the ratio of supply to demand, was 33.5% and 31.8%, respectively. If both systems are implemented at the same time, higher water savings can be achieved, with a total of 929.24 kL/annum and a WSE of 65.3%. This is feasible as there is no overlap of the catchment areas for the two systems. Looking at the total average water consumption of the school (2 251.78 kL), which includes all uses of water, the WSE is 41.3%. The full demand for November, December, January and March can also be met by both systems together.

These results are in line with the study done by Ndiritu et al. (2014) for schools situated in summer-rainfall regions of South Africa. Although widely used, specific WSE percentages are not set factors for system viability, as suggested by Juliana et al. (2019). For their research, the WSE of an RWH system in a public facility in Palembang (Indonesia) was calculated as 29%. However, the authors deemed this ratio too low, and the system not viable, in the context of their study, as opposed to Stec and Zeleňáková (2019) for a Polish case study with the same WSE of 29%, where it was considered viable. Hence, feasible WSEs (like many RWH considerations) are case-dependent and have an element of subjectivity. In the Duffs Road Primary School situation, the WSE for both systems investigated separately and together were considered viable, as considerable volumes of potable water can be replaced.

Tanks selected for implementation for each system are shown in Tables 2 and 3 and the sizing process followed a mass balance approach.

The monthly water savings (due to replacing potable water by rainwater), cost, and carbon emissions were calculated using the case study data (historical rainfall, catchment areas) and the components used for construction and operation as presented in the Methodology section. These findings are summarized in Tables 4 and 5 for Systems 1 and 2, respectively.

From Tables 4 and 5 it can be seen that both systems have similar monthly and yearly rainwater-harvesting potentials and can make a considerable difference in replacing potable water for toilet flushing. The carbon emissions for System 1 are comparable with those of System 2 in the construction stage. However, that is not the case when considering the operational stage for this system (see environmental analysis). The implementation of both systems would save, in addition to the 929.24 kL/year (with an overall WSE of 65.2%), about 56 588.39 ZAR/annum, and GHG emissions of 380.15 kg CO_2/year. However, even the collective implementation of pumped and gravity-fed systems (Systems 1 and 2 together) at the school would still require supplemental municipal water for about 8 months of the year.

Table 4. Monthly and annual savings – System 1

Month	Water savings (kL)	Cost savings (ZAR)	Carbon emission reductions from replacing potable water (kg CO_2)
January	63.17	3 264.98	25.84
February	37.73	2 504.99	15.44
March	51.29	2 493.14	20.98
April	45.08	2 717.05	18.44
May	13.82	1 744.49	5.65
June	8.55	875.64	3.50
July	11.91	1 392.97	4.87
August	14.62	1 717.26	5.98
September	34.45	2 103.35	14.09
October	48.26	3 058.41	19.74
November	85.00	4 287.55	34.77
December	62.87	2 577.64	25.72
Total	**476.76**	**28 737.45**	**195.04**

Table 5. Monthly and annual savings – System 2

Month	Water savings (kL)	Cost savings (ZAR)	Carbon emission reductions from replacing potable water (kg CO_2)
January	60.87	3 180.92	24.90
February	36.36	2 454.78	14.87
March	49.43	2 424.88	20.22
April	43.44	2 657.06	17.77
May	13.32	1 726.09	5.45
June	8.24	864.26	3.37
July	11.48	1 377.12	4.70
August	14.09	1 697.81	5.76
September	33.19	2 057.51	13.58
October	46.50	2 994.19	19.02
November	75.00	3 922.35	30.68
December	60.58	2 493.98	24.78
Total	**452.48**	**27 850.94**	**185.11**

Economic analysis

The economic investigation used cost savings and system capital costs to estimate the return-on-investment period for both RWH systems, and these are summarized in Table 6.

From Table 6, it can be seen that while the pumped system (System 1) provided higher cost savings, it was also more expensive to implement. Conversely, System 2 (the gravity-fed system) had fewer components; hence, was more cost-effective. Ultimately, this resulted in a lower repayment period. The difference, however, is not large. For RWH systems that require pumping, the scale of the catchment area and the volume of rainwater matters, as larger volumes harvested allow for more efficient pumping (Vieira et al., 2014). This seems to be the case for the local case study.

For System 1, it was found that the yearly pump operation costs amounted to 806.03 ZAR (due to the likely number of flushes over sessional school days). Noting that the average yearly municipal consumption for the period 2018 to 2020 was 16 812.55 kWh (or 33 925.13 ZAR/annum in costs), the implementation of a pumped RWH system would cause a 2.3% electricity consumption increase and a 2.4% cost increase at the school (increasing the bill to 34 731.16 ZAR/year). Thus, the pumps would not present a significant increase in the municipal energy usage at Duffs Road Primary School. Furthermore, the cost of running the system pumps (806.03 ZAR/annum) was found to be substantially less than the annual cost savings introduced by the RWH system (28 737.45 ZAR/annum). Thus, both systems were found to be economically viable. The comparison to a Brazilian study undertaken by Antunes and Ghisi (2020) shows that results for the criteria considered are in the same range (see Table 7).

Environmental analysis

The total carbon footprint was divided by the final carbon emission savings (per system) to evaluate the period before each system would begin to achieve a reduction, mainly by savings achieved due to the replacement of potable water. However, for System 1, pump operation would always produce carbon emission burdens. Hence, it was necessary to assess the operational energy needs and the associated carbon footprint of the pumps. Table 8 summarizes the major environmental outcomes for the proposed RWH implementation.

System 1 (the pumped system) achieved higher water and cost savings. However, the presence of more components, as well as the energy needed for pumping, resulted in a higher carbon footprint than the gravity-fed system. The presence of pumps under this

Table 6. Economic outcomes

RWH outcome	System 1	System 2	Optimal system
Water savings	476.76 kL/annum	452.48 kL/annum	System 1
Cost savings	28 737.45 ZAR/annum	27 850.94 ZAR/annum	System 1
Capital costs	170 472.06 ZAR	135 046.25 ZAR	System 2
Operational costs	806.03 ZAR/annum	Nil	System 2
Return period	5.93 years	4.85 years	System 2

Table 7. Comparison of results

Outcome	Antunes and Ghisi (2020) (low-demand schools)	Current research
Potential water savings (L/day)	542–1 574	System 1: 1 306. 2 System 2: 1 239.7
Payback period (months)	46–83	System 1: 71 System 2: 58
Overall energy consumption (kWh/(learner·month))	0.31–66.47	1.40–2.78

Table 8. Environmental outcomes from RWH implementation

RWH outcome	System 1	System 2	Optimal system
Water savings	476.76 kL/annum	452.48 kL/annum	System 1
Carbon emission	180 kg CO_2/year (net emissions)	–185.11 kg CO_2/year (savings)	System 2
System carbon footprint (embedded carbon)	2 188.02 kg CO_2	1 914.64 kg CO_2	System 2
Operational carbon footprint	375.14 kg CO_2/annum	nil	System 2
Period before emission reduction	N/A due to pump emissions which are ongoing	10.34 years	System 2

scenario resulted in an operational carbon footprint of 375.14 kg CO_2 per year. When comparing this value to the carbon emissions savings that could be introduced by System 1 (195.04 kg CO_2), the pump emissions exceeded the system savings by 180.10 kg CO_2 per year, but an important potable water volume is saved. This trade-off is another facet of the water–energy–carbon nexus investigated in the literature in the provision and treatment of water (Nair et al., 2014).

When looking at the energy efficiency of System 1, a figure of 0.82 kWh/kL of rainwater harvested was achieved. This figure is in line with published literature (Vieira et al, 2014), where the review showed an energy efficiency range of 0.20–1.40 kWh/kL for harvested rainwater in empirical and theoretical studies. This is much higher when compared with the provision of potable water in the eThekwini Municipality, which requires 0.26 kWh/kL of potable water, even when considering a 30% loss in the distribution network (Buckley et al., 2011). However, when considering alternatives to municipal water, such as groundwater, mine water reclamation, wastewater recycling or desalination, this energy figure is comparable; however, the quality and therefore the limitations in the use of untreated rainwater also need to be taken into consideration. In the international literature, energy requirements for desalination are from 3.00 to 5.00 kWh/kL and for groundwater extraction from 0.14 to 1.02 kWh/kL (Nair et al., 2014). In South Africa desalination figures ranged from 3.97 kWh/kL for the Sedgefield plant to 4.52 kWh/kL for the Albany Coast plant (Turner et al., 2015). For mine water reclamation in South Africa an energy efficiency of 2.16 kWh/kL was obtained (Goga et al., 2019), and locally (Durban Wastewater Recycling Plant) for wastewater recycling about 0.44 kWh/kL is needed (Buckley et al., 2011). Therefore, RWH energy requirements, as shown in this local case study, compare well with most of these alternatives.

Life cycle assessment

The findings of the LCA revealed the impact burdens due to construction and operation of the RWH systems, and are presented in Figs 5 and 6. The 18 impact categories correspond to the numbered categories in Table 9, with 1 on the far left and 18 on the far right.

For System 1 (see Fig. 5), the environmental scores show that the electrical energy used by the pumps accounted for the largest environmental burdens across most of the LCA impact categories. These percentages ranged from 41.5% for freshwater ecotoxicity burdens to 86.3% for stratospheric ozone depletion. Where the pump energy impacts were predominant, the operational burdens outweighed the total and individual burdens due to the construction of the system. This result can be seen for Impact Categories 1–9 and 13–15 (12 out of 18 groups). When analysing freshwater and marine ecotoxicity (Categories 11 and 12) and fossil resource scarcity (Impact Category 17), the total assembly/construction burdens were higher than operational burdens, yet energy usage was still found to be the highest individual impact contributor. This was due to the pump electricity having greater environmental burdens than any individual component in construction. For the terrestrial ecotoxicity grouping, pump manufacturing was found to generate 45.8% of the total burden, while the energy usage accounted for 29.5% of impacts. In terms of mineral resource scarcity, pump manufacture was at 59.4%, and electricity usage at 9.9% of the total impacts. As the pumps were made of cast iron (body), stainless steel (shaft), and brass (impeller), the greatest burdens stemmed from brass production. For the final impact category (water consumption), neither pump construction nor usage had the greatest burdens. Rather the assembly/production of the three 15 kL storage tanks generated the majority of the environmental concerns (36.1%), followed by the two 20 kL tanks (32.1%) and pump usage (26%).

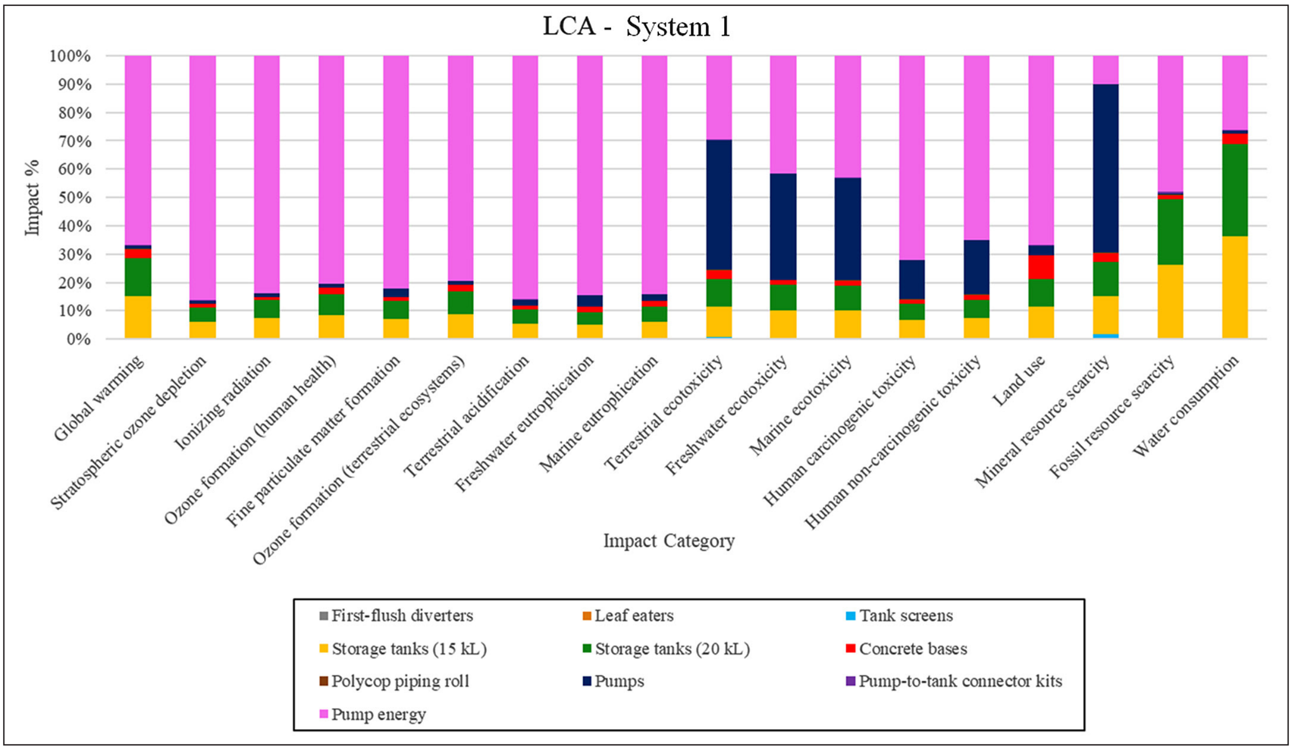

Figure 5. Environmental burdens – System 1

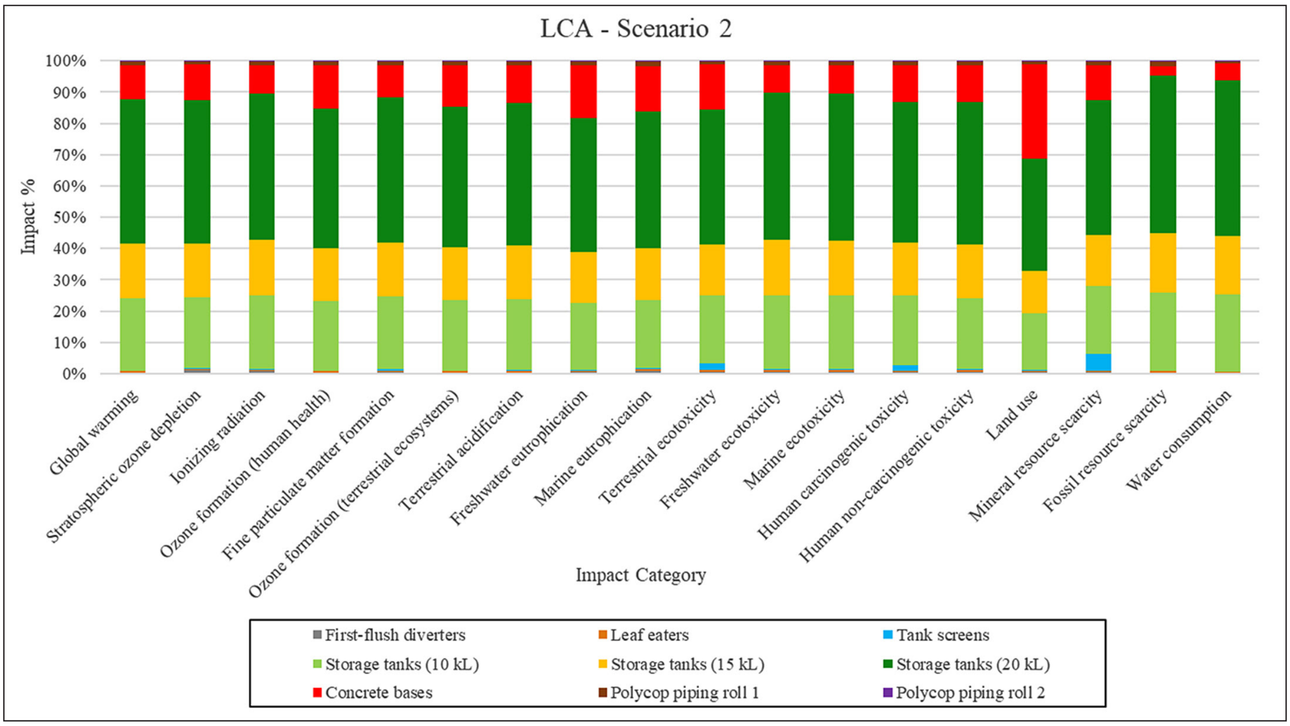

Figure 6. Environmental burdens – System 2

The environmental profile for System 2 (see Fig. 6) summarized the total potential impacts per kL of harvested rainwater, much like for the first system. It is evident from Fig. 6 that the two 20 kL storage tanks accounted for the highest individual burdens for all 18 impact categories, ranging from 36% (in land use) to 50.4% of the total effects (for fossil resource scarcity). In other words, the two 20 kL tanks made up (at minimum) over a third and, at most, slightly over half the total environmental burdens for System 2. The other two storage tank types (10 and 15 kL) also displayed important contributions to all impact categories included, followed by the concrete bases for all tanks. The other components have small environmental burdens, with the pre-filtration mechanisms (first-flush diverters and leaf eaters) and the Polycop pipes being insignificant, since these percentages did not even display at the given scale in Fig. 6. The exception was the tank screen's environmental burden for terrestrial ecotoxicity, human carcinogenic toxicity, and mineral resource scarcity (shown in light blue). However, even these burdens were relatively low when compared to the proportions from the storage tanks and concrete. Therefore, storage, even though it improves reliability

Table 9. Environmental scores for System 1 and 2 expressed per 1 kL rainwater harvested

Impact category	Unit	System 1	System 2	% Difference
1. Global warming	kg CO2 eq	1.310	0.398	106.8
2. Stratospheric ozone depletion	kg CFC-11 eq	79.9×10^{-8}	9.49×10^{-8}	157.5
3. Ionizing radiation	kBq Co-60	47.3×10^{-3}	6.71×10^{-3}	150.3
4. Ozone formation – human health	kg NO_x eq	4.79×10^{-3}	0.84×10^{-3}	140.3
5. Fine particulate matter formation	kg PM2.5 eq	3.06×10^{-3}	0.436×10^{-3}	150.1
6. Ozone formation – terrestrial ecosystems	kg NO_x eq	4.85×10^{-3}	0.89×10^{-3}	138.0
7. Terrestrial acidification	kg SO_2 eq	9.70×10^{-3}	1.09×10^{-3}	159.6
8. Freshwater eutrophication	kg P eq	75.0×10^{-5}	8.2×10^{-5}	160.6
9. Marine eutrophication	kg N eq	4.56×10^{-5}	0.59×10^{-5}	154.2
10. Terrestrial ecotoxicity	kg 1,4-DCB	3.12	0.73	124.2
11. Freshwater ecotoxicity	kg 1,4-DCB	0.063	0.013	131.6
12. Marine ecotoxicity	kg 1,4-DCB	0.083	0.016	135.4
13. Human carcinogenic toxicity	kg 1,4-DCB	0.083	0.011	153.2
14. Human non-carcinogenic toxicity	kg 1,4-DCB	1.601	0.239	148.0
15. Land use	m^2a crop eq	13.5×10^{-3}	3.9×10^{-3}	110.3
16. Mineral resource scarcity	kg Cu eq	0.0036	0.0010	113.0
17. Fossil resource scarcity	kg oil eq	0.534	0.257	70.0
18. Water consumption	m^3	0.0108	0.0074	37.4

of gravity-fed RWH systems, carries the highest environmental burdens, which is another trade-off in the performance of these systems. Rashid et al. (2022) found similar trends with regards to storage tanks and, furthermore, different tank materials were assessed, with HDPE tanks performing environmentally better as compared to LDPE (similar to the ones used in this study), steel and ferrocement tanks.

A comparison of the two RWH systems in terms of the actual environmental scores calculated is presented in Table 9, showing the real difference due to the pumping and associated environmental impacts from electricity usage in South Africa.

For all the impact categories modelled, the scores for System 1 are an order of magnitude larger than those for System 2, with the impact categories linked to South African electricity production from coal showing the largest differences. This result also mirrors results from other local LCA studies of water systems (e.g. Friedrich et al., 2009, for conventional systems and Goga et al., 2019, for alternative water sources), underlining the role of energy in the environmental performance of different water systems. Hence, alternative systems for energy provision for RWH, like solar panels, should be investigated. The LCAs undertaken clearly show that if one targets improvement of System 1, energy burdens have to be addressed, whereas for System 2, storage tank alternatives, and in particular HDPE tanks, should be investigated.

CONCLUSION

This study assessed in detail the performance of two RWH systems for toilet flushing at a large school in the eThekwini Municipality, South Africa. Two systems were investigated: one using pumps (System 1) and one gravity-fed (System 2). Both systems aimed to supply water for toilet flushing at the ablutions building only. The viability of the two systems was assessed in terms of their water-saving potential/efficiency and economic and environmental criteria. In terms of rainwater collection, the pumped system harvested 476.8 kL/annum with an estimated WSE of 33.5%, while that of the gravity-fed system was at 31.8%, with 452.5 kL/annum harvested. Together, they supplied about 929.2 kL/annum with a combined WSE of 65.3% for toilet flushing and 41.3% when considering total water consumption of the school. While the individual proportions may seem low (accounting for approximately a third of demand), both systems were deemed viable due to the significant water and municipal cost savings. Furthermore, when implemented together they could save about two-thirds of the flush water needed. However, municipal water would still be required for about 8 months of the year for toilet flushing, even though the storage tanks would give more reliability.

Both systems are viable when considering economic performance. System 1 (pumped operation) would increase the current municipal energy costs by only 2.4%, as pump operation expenses were estimated to be around 806 ZAR/annum. Comparing this to the yearly water savings of 28 737.50 ZAR further demonstrates the economic feasibility of the pumped system. This is close to the 27 851 ZAR achieved by the gravity-fed system. The repayment periods for both systems were similar, but there was a marked difference between the pumped and the gravity-fed systems in terms of environmental performance. For System 1, the significant tradeoff was the increased carbon emissions generated from pump usage (375.14 kg CO_2eq/annum), which would exceed the potential carbon emission savings from the replacement of municipal potable water by 180.10 kg CO_2 eq every year. In the construction/assembly stage, the manufacturing of RWH components would generate carbon emissions (embedded carbon). For this case study, both systems had comparable burdens, showing that the additional pumps needed for System 1 did not result in large amounts of embedded carbon. The pumping, however, allowed an increase in harvested rainwater and for another third of the demand for toilet-flush water to be met. This is another aspect of the water–energy–carbon nexus manifested in the local context, and is an important trade-off that needs to be considered for RWH systems. When comparing the energy demands of System 1 with alternatives like groundwater extraction, recycling of wastewater, mine-water reclamation and desalination, the energy needed for pumping of the rainwater harvested was lower or within range.

Pumping and the associated energy was also a key aspect of the LCA, and the environmental modelling showed that System 1 had a higher order of magnitude, when scores for all 18 impact categories were considered, mainly because of pumping energy. It was also obvious that the impacts of pump operation overshadowed those of manufacturing all other system components, and a pumped RWH system would always be more damaging environmentally in comparison to a gravity-fed system. However, System 1 can be further optimized to reduce energy consumption and alternative renewable energy sources should be considered. For the gravity-fed system, the highest burdens were found to come from the manufacturing of the storage tanks and their concrete support platforms. Thus, it shows that in gravity-fed systems, storage increases the reliability of the system in terms of rainwater supply, but carries the highest environmental burden for these systems. This is another trade-off to be included in decision-making.

For the school investigated, as well as other similar schools (with a large number of learners and situated in hilly areas), it is recommended that a gravity-fed system be prioritized given its economic and environmental viability in this context. Furthermore, increases in water tariffs will provide higher municipal water cost savings for the same physical amount of water harvested and used. Hence, RWH systems with similar capacities/characteristics as specified in this study may have improved economic viability in the future. Considering the cost savings, as well as environmental benefits and burdens, it is recommended that disadvantaged schools (and schools likely to garner higher savings based on their local characteristics enabling gravity-fed systems) be prioritized for governmental RWH subsidies.

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