Life cycle assessment of rainwater harvesting in Brazilian urban residences

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Highlights:

- Increasing reuse targets in rainwater harvesting systems significantly reduce environmental impacts, outperforming traditional water supply methods.
- More complex rainwater systems with multiple components achieve environmental benefits at higher reuse levels, demonstrating scale-dependent efficiency.
- A comprehensive analysis across diverse scenarios confirms the predominant benefits of rainwater harvesting, with few cases showing greater impacts than baseline.

Keywords: green and blue infrastructure; water reuse; environmental performance

INTRODUCTION

Urban water management faces escalating challenges due to population growth, increased consumption, and the unpredictable effects of climate change, creating a need for innovative, sustainable approaches to reduce stress on traditional water supply systems (Oral et al., 2020). One such solution is rainwater harvesting, which offers a reliable and environmentally sustainable alternative for non-potable water uses. Rainwater harvesting reduces dependence on conventional water sources and offers a sustainable solution for alleviating urban water scarcity, showing lower environmental impacts compared to centralized mains water systems, particularly in tropical climates (Leong et al., 2019; Lv et al., 2021).

In addition to mitigating stormwater runoff and contributing to groundwater preservation, rainwater harvesting systems reduce dependency on centralized water supplies, leading to substantial energy savings and CO_2 emissions reductions (Ghimire and Johnston, 2019). The integration of renewable energy sources and innovative storage solutions can further enhance the performance of these systems (Teston et al., 2022). Despite these benefits, there remains a need for standardized Life Cycle Assessment (LCA) methodologies and a more holistic assessment of rainwater harvesting systems to fully capture their potential advantages (Raimondi et al., 2023). This study applies LCA to analyse rainwater harvesting systems across five diverse urban settings in Campo Grande, Mato Grosso do Sul, Brazil, aiming to estimate their environmental impact.

METHODOLOGY

The LCA was conducted in alignment with ISO 14040 (2006) standards, applied using SimaPro 9.2 software. The primary objective of this LCA was to conduct a comprehensive environmental performance evaluation, focusing on identifying optimization opportunities and potential environmental impact reductions in decentralized water reuse systems. The functional unit of this study is defined as the supply of one cubic meter of water. Each scenario was analysed to assess how effectively it balanced the supply of harvested rainwater with the demand for water usage.

Our evaluation considers a range of scenarios in which rainwater harvesting systems supply water, aiming to achieve reductions in drinking water usage from the municipal supply system by 20% to 80%. We also include a baseline scenario representing the drinking water supply system. While direct comparisons between rainwater and drinking water are inappropriate due to quality differences, our comparison focuses solely on lower-quality demands such as toilet flushing and cleaning. Table 1 provides an overview of the key characteristics of the case studies.

Case Study	**Characteristics**	**Average water consumption ($m^3.month^{-1}$)**	**Roof catchment area (m^2)**	**Cistern volume (m^3)**	**Water reuse finalities**
1	A 19-story residential building	300	520	20	Cleaning and gardening (common areas)
2	School	100	200	10	Cleaning, gardening, and production of handmade paper
3	Single-family residence (gravity only)	15	50	1,4	Cleaning and maintaining the water level in a swimming pool, compensating for evaporation.
4	Single-family residence	15	75	1,95	Cleaning and gardening
5	Single-family residence	20	170	10	Cleaning, gardening, toilet flushing, and laundry

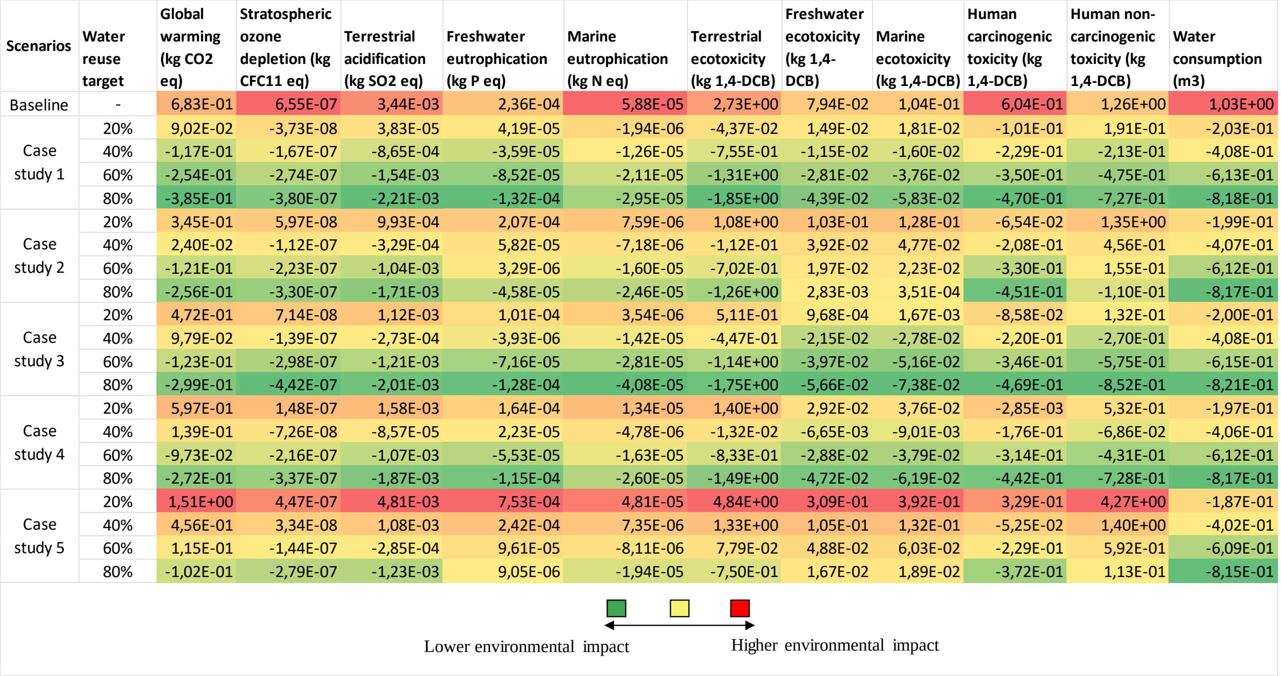
Table 1 – Overview of the scenarios selected in the analysis

Background data in the life cycle inventory considered the ecoinvent™ database version 3.7.1 with allocation at point of substitution (Alloc Def), while foreground data were based on primary sources and representative literature. The impact assessment method selected was the ReCiPe 2016 Midpoint method (Hierarchist - H), with global coverage, version 1.13. A total of 10 impact categories were selected for analysis.

Both the construction and operational phases of the systems were analysed, detailing the materials and components used such as PEAD, PVC, resin, fiberglass, along with pumps, valves, and piping. The assessment also includes electricity consumption and other significant operational inputs. Systems typically consist of cisterns, water leaf catchers, tablet chlorinators, 25-micron water filters, 0.5 HP water pumps, water level sensors, and taps. In some cases, an upper reservoir is also used to receive and distribute rainwater.

RESULTS AND CONCLUSIONS

Figure 1 shows the LCA results, evaluated across multiple impact categories. A colour scale was used to facilitate the visualization of rankings between each environmental impact category. When comparing the environmental impacts of rainwater harvesting systems to the baseline drinking water supply system, it is evident that higher water reuse targets generally result in decreased environmental impacts, indicating greater benefits with increased reuse. Specifically, environmental improvements are observed across all reuse targets for case studies 1, 3, and 4. For case study 2, benefits emerge only when the reuse target reaches 40%, and for case study 5, advantages are apparent from a 60% reuse target onwards.



Scenarios	Water reuse target	Global warming (kg CO2 eq)	Stratospheric ozone depletion (kg CFC11 eq)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)	Terrestrial ecotoxicity (kg 1,4-DCB)	Freshwater ecotoxicity (kg 1,4-DCB)	Marine ecotoxicity (kg 1,4-DCB)	Human carcinogenic toxicity (kg 1,4-DCB)	Human non-carcinogenic toxicity (kg 1,4-DCB)	Water consumption (m3)
Baseline	-	6,83E-01	6,55E-07	3,44E-03	2,36E-04	5,88E-05	2,73E+00	7,94E-02	1,04E-01	6,04E-01	1,26E+00	1,03E+00
Case study 1	20%	9,02E-02	-3,73E-08	3,83E-05	4,19E-05	-1,94E-06	-4,37E-02	1,49E-02	1,81E-02	-1,01E-01	1,91E-01	-2,03E-01
	40%	-1,17E-01	-1,67E-07	-8,65E-04	-3,59E-05	-1,26E-05	-7,55E-01	-1,15E-02	-1,60E-02	-2,29E-01	-2,13E-01	-4,08E-01
	60%	-2,54E-01	-2,74E-07	-1,54E-03	-8,52E-05	-2,11E-05	-1,31E+00	-2,81E-02	-3,76E-02	-3,50E-01	-4,75E-01	-6,13E-01
	80%	-3,85E-01	-3,80E-07	-2,21E-03	-1,32E-04	-2,95E-05	-1,85E+00	-4,39E-02	-5,83E-02	-4,70E-01	-7,27E-01	-8,18E-01
Case study 2	20%	3,45E-01	5,97E-08	9,93E-04	2,07E-04	7,59E-06	1,08E+00	1,03E-01	1,28E-01	-6,54E-02	1,35E+00	-1,99E-01
	40%	2,40E-02	-1,12E-07	-3,29E-04	5,82E-05	-7,18E-06	-1,12E-01	3,92E-02	4,77E-02	-2,08E-01	4,56E-01	-4,07E-01
	60%	-1,21E-01	-2,23E-07	-1,04E-03	3,29E-06	-1,60E-05	-7,02E-01	1,97E-02	2,23E-02	-3,30E-01	1,55E-01	-6,12E-01
	80%	-2,56E-01	-3,30E-07	-1,71E-03	-4,58E-05	-2,46E-05	-1,26E+00	2,83E-03	3,51E-04	-4,51E-01	-1,10E-01	-8,17E-01
Case study 3	20%	4,72E-01	7,14E-08	1,12E-03	1,01E-04	3,54E-06	5,11E-01	9,68E-04	1,67E-03	-8,58E-02	1,32E-01	-2,00E-01
	40%	9,79E-02	-1,39E-07	-2,73E-04	-3,93E-06	-1,42E-05	-4,47E-01	-2,15E-02	-2,78E-02	-2,20E-01	-2,70E-01	-4,08E-01
	60%	-1,23E-01	-2,98E-07	-1,21E-03	-7,16E-05	-2,81E-05	-1,14E+00	-3,97E-02	-5,16E-02	-3,46E-01	-5,75E-01	-6,15E-01
	80%	-2,99E-01	-4,42E-07	-2,01E-03	-1,28E-04	-4,08E-05	-1,75E+00	-5,66E-02	-7,38E-02	-4,69E-01	-8,52E-01	-8,21E-01
Case study 4	20%	5,97E-01	1,48E-07	1,58E-03	1,64E-04	1,34E-05	1,40E+00	2,92E-02	3,76E-02	-2,85E-03	5,32E-01	-1,97E-01
	40%	1,39E-01	-7,26E-08	-8,57E-05	2,23E-05	-4,78E-06	-1,32E-02	-6,65E-03	-9,01E-03	-1,76E-01	-6,86E-02	-4,06E-01
	60%	-9,73E-02	-2,16E-07	-1,07E-03	-5,53E-05	-1,63E-05	-8,33E-01	-2,88E-02	-3,79E-02	-3,14E-01	-4,31E-01	-6,12E-01
	80%	-2,72E-01	-3,37E-07	-1,87E-03	-1,15E-04	-2,60E-05	-1,49E+00	-4,72E-02	-6,19E-02	-4,42E-01	-7,28E-01	-8,17E-01
Case study 5	20%	1,51E+00	4,47E-07	4,81E-03	7,53E-04	4,81E-05	4,84E+00	3,09E-01	3,92E-01	3,29E-01	4,27E+00	-1,87E-01
	40%	4,56E-01	3,34E-08	1,08E-03	2,42E-04	7,35E-06	1,33E+00	1,05E-01	1,32E-01	-5,25E-02	1,40E+00	-4,02E-01
	60%	1,15E-01	-1,44E-07	-2,85E-04	9,61E-05	-8,11E-06	7,79E-02	4,88E-02	6,03E-02	-2,29E-01	5,92E-01	-6,09E-01
	80%	-1,02E-01	-2,79E-07	-1,23E-03	9,05E-06	-1,94E-05	-7,50E-01	1,67E-02	1,89E-02	-3,72E-01	1,13E-01	-8,15E-01

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Lower environmental impact ⟷ Higher environmental impact

Figure 1 – LCA results across the selected impact categories from Recipe (2016) method (higher scores indicate worst performance)

This pattern suggests that systems with high water consumption or minimal material used during construction, such as in case studies 1 and 3-4 respectively, tend to be more environmentally favourable. In contrast, more complex systems, such as those in case studies 2 and 5 which require additional components, necessitate higher reuse rates to mitigate their greater environmental impacts.

Despite these challenges, out of 360 analysed data points spanning all case studies, targets, and categories, only 14 showed a higher environmental impact than the baseline scenario, affirming the predominantly positive environmental potential of rainwater harvesting across a variety of contexts. These exceptions occurred primarily in systems with low water reuse rates or those where the complexity of the installation introduced additional materials and energy demands.

Overall, the results suggest that rainwater harvesting has strong potential to reduce environmental impacts, but careful consideration must be given to system complexity, especially when scaling up. Expanding the use of LCA in system design could enhance decision-making processes, ensuring that rainwater harvesting systems provide maximum environmental benefits while addressing urban water challenges.

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