Cost-effective rainwater harvesting system in the Metropolitan Area of Barcelona

M. Violeta Vargas-Parra, María Rosa Rovira, Xavier Gabarrell and Gara Villalba

ABSTRACT

Expected population growth will result in increasing water demand. The consequences could potentially jeopardise water resource availability especially in urban areas and significantly increase costs. Rainwater harvesting (RWH) systems can aid not only in meeting water demand partially, but also doing so in a more cost-effective and environmentally friendly manner than other techniques. Although the reduction of environmental burdens is fairly obvious, the question for urban planners and consumers remains: are RWH systems economically feasible? This paper investigates cost-effectiveness of eight different scenarios in the Metropolitan Area of Barcelona. To do so, monetary investment is quantified to provide rainwater for laundry purposes. Results indicate that high density scenarios are financially the most suitable choices (higher net present value and shorter payback time) given that: more users mean more savings from laundry additive consumption. Further studies should consider which are the variables that have a greater effect on the financial appraisal. Similar to inflation rate, specific attention should be paid to the costs associated with the storage tank location. Included on the savings side should be the no tap water consumption effect on the water bill, along with special attention to tap water prices in the area of study.

Key words | economic assessment, rainwater harvesting, smart cities, urban planning, water planning

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INTRODUCTION

Water is a renewable resource but its availability is limited. Moreover, population growth increases water demand making urban areas more vulnerable to water stress (Angrill *et al*. 2011). Unconventional water resources, such as rainwater harvesting (RWH), among others, are significant contributors in the pursuit of urban water self-sufficiency (Rygaard *et al*. 2011b).

Water resources management is an essential component of social and economic development (United Nations Development Programme 2006) and the unsustainable exploitation of this resource represents a menace to human development (World Water Assessment Programme 2009). Specifically, the UN declared 2013 the Year of International Water Cooperation (United Nations General Assembly 2010) and in this frame, it is important to highlight that D'Orville (UNESCO Assistant Director-General for Strategic Planning) indicated that: 'Private and public organisations at all different levels must be involved, together, towards common end and mutual benefits for a balanced and fair management and use of water resources' (D'Orville 2011).

RWH is an ancient technique that dates back to the third millennium BC in India, 2000 BC in Israel and 1700 BC in the Mediterranean area (Gould & Nissen-Petersen 1999) and has been widely adopted and more especially applied in areas with limited water availability, either in rural or urban areas. Several studies in urban areas have been carried out to evaluate RWH performance by different approaches.

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As an alternative source of water for domestic laundry, Angrill et al. (2011) evaluated the environmental impact of different scenarios applying RWH systems in urban Mediterranean areas. The efficiency of the systems have also been determined and studied in different approaches and locations around the world. Herrmann & Schmida (2000) calculated the water balance of a one-family house and a multi-storey building in Germany, Ghisi & Mengotti de Oliveira (2007) combined greywater and RWH to evaluate the efficiency of these systems (combined or separated), performing an economic analysis to estimate potable water savings in Brazil, and Coombes et al. (2000) analysed the quality of rainwater and hot water systems at a water sensitive urban redevelopment of 27 houses in Australia.

Other authors intend to go further and have developed computer models to simulate potential water supply (Morales-Pinzón et al. 2012b), water saving efficiency (Villarreal & Dixon 2005), and hydraulic and cost performance (Roebuck & Ashley 2006).

Others authors have studied the quality of rainwater and the applicability of RWH systems in urban areas (Sazakli et al. 2007; Lye 2009; Farreny et al. 2011b; Mendez et al. 2011). Meanwhile, others have researched its economic facet, in the pursuit of the optimal tank size, such as Campisano & Modica (2012) in Sicily, Fengtai & Xiaochao (2012) in China, Imteaz et al. (2011), Rahman et al. (2010) and Zhang et al. (2009) in Australia. Morales-Pinzón et al. (2012a) analysed the optimal material for the tank in Barcelona and Coombes et al. (2003) studied a dual system (RWH and tap water).

All the economic studies consider the initial investment or capital cost; however, the operating expenses are often limited to electricity usage and pump replacement (Leggett et al. 2001; Coombes et al. 2003; Liaw & Tsai 2004; Mitchell et al. 2005; Roebuck & Ashley 2006; Ghisi & Mengotti de Oliveira 2007; Marsden Jacob Associates 2007; Rahman et al. 2010; Farreny et al. 2011a; Roebuck et al. 2011; Rygaard et al. 2010, 2011b; Morales-Pinzón et al. 2012a, c), neglecting labour costs and other items that have to be replaced within the life of the system. Moreover, at the time of this writing we could not find any study that included the removal cost of these systems.

Tap water hardness has been proven to reduce the life-span of home appliances (Van der Bruggen et al. 2009; Godskesen et al. 2012) and to increase detergent consumption (Rygaard et al. 2011a). Tap water in Barcelona, with values above 300 ppm, is in the range of very hard water, according to Durfor & Becker's (1964) classification table. Derived from this, Morales-Pinzón et al. (2014) studied the potential replacement of tap water with rainwater in different cities of Spain.

Recently, RWH facilities have been installed in public and private buildings in the Mediterranean area, but currently it is not common and one of the main reasons is the lack of information related to its economic aspects.

This paper studies the life cycle, economic and financial aspects of eight RWH scenarios; from the construction, through its use and including end-of-life, as an alternative supply of domestic laundry water demand in the Metropolitan Area of Barcelona (MAB).

The paper is structured in three parts. First, the methods section describes the design of each scenario, including rainwater offer and laundry demand, data sources and selection criteria, data inventory as well as a description of the economic and financial analysis employed. Second, we present the financial results and a discussion of the findings. Finally, the results are summarised in the conclusions, showing as well the limitations and some guidelines for future research on this matter.

METHODS

Scenario design

Domestic RWH systems have three basic components (Figure 1): (1) a storage facility (aboveground or underground tank); (2) a catchment area (rooftop or courtyards and similar compacted or treated surfaces); and (3) a delivery system that transports water from the catchment area to the storage facility and from the storage facility to the building (Worm & Hattum 2006).

With regard to this study, rainwater is collected from rooftops and it is considered for one exclusive use: domestic laundry.

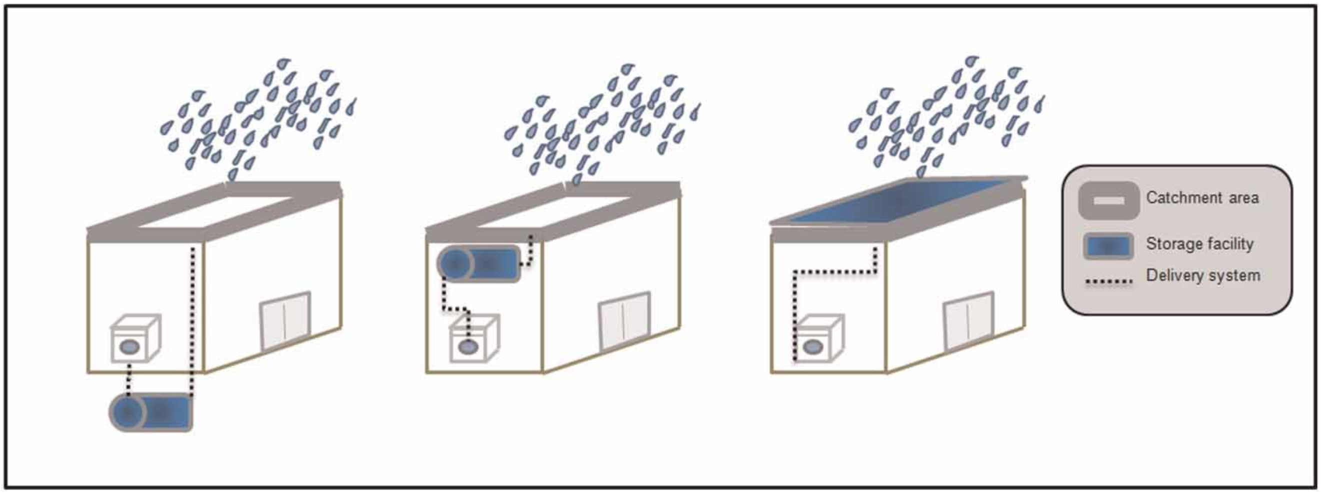

Figure 1 | Basic components of a domestic RWH system.

Neighbourhoods in Mediterranean climates are represented by two proposed different density models: low and high density models, based on two contrasting population densities (10 and 90 hab/km^2 correspondingly) within urban areas. Each density model considers three different scenarios based on the storage location and an extra scenario that considers a group of buildings of the density in question.

Low density models consider a single-family home with 250 m^2 of collection surface (rooftop). High density models examine a five-storey building with 24 home-apartments and 700 m^2 of collection surface (Figure 2). According to the average household size of Mediterranean climate urbanisations, each household has 2.65 inhabitants (Australian Government 2010; Eurostat 2014; US Census Bureau 2014).

Tables 1 and 2 summarise the eight different scenarios, showing the two density models (low and high), storage size and location, and the amount of rainwater that can be provided to satisfy laundry necessities per each scenario.

Rainwater offer and laundry demand

Rainwater is, by nature, soft water with few minerals compared to surface and groundwater. Farreny et al. (2011b) found that the rainwater collected in the MAB is softer than tap water, and therefore, an advantageous substitute for laundry use since soft water requires less detergent, softener and machinery maintenance.

Rainwater offer, laundry water demand and storage tank size were calculated using a simulation model (Plugrisost) developed by Morales-Pinzón et al. (2012c). Rainwater offer

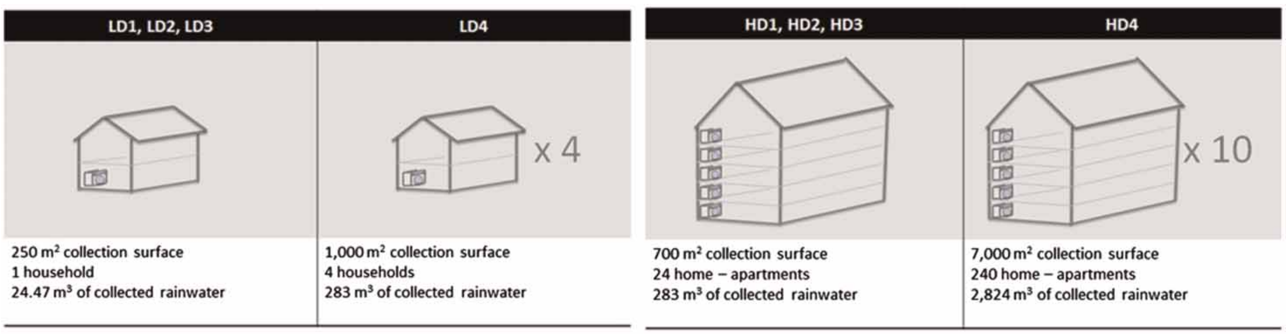

Figure 2 | Density models. *Source:* Vargas-Parra et al. (2013).

Table 1 | Low density scenarios description

	LD1	LD2	LD3	LD4
Scale	1 Household	1 Household	1 Household	4 Household
Tank	(5 m^3) Underground	(5 m^3) Below roof tank	(9 m^3) Spread on roof	(20 m^3) Underground
Collecting area	250 m^2	250 m^2	250 m^2	1,000 m^2
Rainwater for laundry per year	24.4 m^3	24.4 m^3	24.4 m^3	99 m^3
Laundry water demand per year	25 m^3	25 m^3	25 m^3	100 m^3
Offer/demand	98%	98%	98%	99%

Table 2 | High density scenarios description

	HD1	HD2	HD3	HD4
Scale	1 Building: 24 households	1 Building: 24 households	1 Building: 24 households	10 Building: 240 households
Tank	(20 m^3) Underground	(20 m^3) Below roof tank	(21 m^3) Spread on roof	(209 m^3) Underground
Collecting area	700 m^2	700 m^2	700 m^2	7,000 m^2
Rainwater for laundry per year	283 m^3	283 m^3	283 m^3	2,824 m^3
Laundry water demand per year	600 m^3	600 m^3	600 m^3	6,000 m^3
Offer/demand	47%	47%	47%	47%

calculations are based on a daily time series of rainfall (from 1991 to 2010), a roof-runoff coefficient estimated at 0.9 (Singh 1992) and the area of collection.

Water demand calculations considered the water consumption of five wash loads (per week and household) of an A+ eco-label washing machine (Angrill *et al.* 2011), as well as a lifespan of 50 years for the RWH system (Roebuck & Ashley 2006).

Data source and criteria

Material, labour, tools and equipment prices were obtained primarily from the Technology of Construction of Catalonia Institute database (ITeC 2012), that provided us with actualised data from the construction sector in Catalonia and is one of the most used catalogues from experts in the area (Oliver-Solà *et al.* 2009a, b; Farreny 2010; Angrill *et al.* 2011; Farreny *et al.* 2011a; Mendoza *et al.* 2012; Morales-Pinzón *et al.* 2012a; Sanjuan-Delmás *et al.* 2013; Petit-Boix *et al.* 2014). The tank and pump prices were obtained directly from expert suppliers of RWH materials in Catalonia. To be more accurate and whenever possible, we calculated an average price from ITeC and the Guadalajara's mid-level Architecture official college database (Colegio Oficial de Aparejadores 2012), another reliable source of prices in the sector, but this was only possible for a few items. After a thorough selection of inputs from these sources, a validation phase was done by consulting a senior professional of water installations in the MAB.

Each scenario includes a different quantity of the inputs contained in Table 3, depending on the size and configuration of the scenario.

Data inventory

Material and services necessary for each of the three life cycle stages of the RWH system as well as their costs are summarised in Table 3. As mentioned above, to be consistent with the life cycle approach, we included the removal cost of the system (deconstruction services and transport of deconstructed materials) at the end-of-life stage.

Table 3 | Cost inventory (Euros)

Stage	Input description		Units	Cost in euros: Material	Cost in euros: Labour	Cost in euros: Total	Lifetime
Construction stage	Prefabricated concrete tank	5,800 litres	unit	2,083		2,083	50
		21,000 litres	unit	5,670		5,670	50
		40,000 litres	unit	11,298			50
		11,600 litres	unit	3,665			50
	Pavement		m^2	14.09	7.42	21.51	50
	Sand backfilling		m^3	27.72	1.26	28.98	50
	Reinforced concrete	For pillars	kg	0.85	0.25	1.1	50
		For walls	kg	0.85	0.4	1.25	50
		For slabs	kg	0.85	0.29	1.13	50
	Waterproofing foil PVC-P with fiberglass.		m^2	19.82	8.22	28.05	50
	Brick		m^2	4.95	13.9	18.85	50
	Mortar		m^2	1.89	13.74	15.63	50
	Polypropylene copolymer pipeline		m	15.79	7.35	23.14	25
	Multistage centrifugal electric pump		unit	500	0	500	10
	Basket type filter pit surface		unit	390		390	5
	Construction services	Excavation of trenches and pits	h	0	7.7	7.7	50
		7 ton truck for soil transportation to a waste management plant	h	0	7.75	7.75	50
		Earthmoving with shovel	h	0	15.77	15.77	50
		24 ton truck for soil transportation to a waste management plant	h	0	4.22	4.22	50
		12 ton, self-propelled crane	h	0	48.98	48.98	50
		20 ton, self-propelled crane	h	0	57.07	57.07	50
		60 ton, self-propelled crane	h	0	109.89	109.89	50
		Journeyman Plumber	h	0	19.05	19.05	50
Use stage	Electricity (yearly)		kWh			0.21	1
	Journeyman Plumber tank cleaning and filter replacement (every 5 years)		h	0	19.05	19.05	5
	Journeyman Plumber cleaning and pump replacement (every 10 years)		h	0	19.05	19.05	10
	Multistage centrifugal electric pump (every 10 years)		unit	500	0	500	10
	Basket type filter pit surface. (every 5 years)		unit	390		390	5
End-of-life stage	Transport of rubble to a waste management facility (50 km)	12 ton transport truck	h	0	38.5	38.5	0
		20 ton transport truck	h	0	48.25	48.25	0
		45 ton semi trailer truck	h	0	88.32	88.32	0
		60 ton semi trailer truck	h	0	100.95	100.95	0
		25 ton semi trailer truck with platform	h	0	37.74	37.74	0
	Construction services	Full demolition, no sorting of waste and load on truck	m^3	0	10.57	10.57	0
		Demolition of retaining wall, load on truck	m^3	0	147.81	147.81	0
		Demolition of slope formation, load on truck	m^3	0	5.91	5.91	0

Economic and financial analysis

The economic assessment is based on the capital cost or initial investment of the materials, labour and tools costs for the construction of the RWH system. After that, during the stage of use, the operating expenses have been thoroughly studied and validated with a senior expert, including energy consumption, replacement, maintenance and labour necessary to keep the system functioning properly until the end of its useful life. For the end-of-life stage we did not find any studies that included the removal cost of the RWH system, which we consider should be included to be consistent with the life cycle perspective and therefore is included in this study.

The savings consisted of the costs saved from avoided use of detergent, fabric conditioner and water softener (Farreny *et al.* 2011b; Rygaard *et al.* 2010, 2011a, b; Godskesen *et al.* 2012). Laundry additive manufacturers recommend a different dose of the product for different water hardness. After studying ten different brands for detergents, five for fabric conditioners and one for water softener, an average dose was calculated for three different levels of water hardness (Table 4).

Financial evaluation of the RWH systems was obtained using three main tools for capital investment (to assist decisions on long-term projects): to determine the current value of the initial investment and all future cash flows, a net present value (NPV) is calculated over the 50 years of lifespan of the system, simultaneously, the calculation of the internal rate of return (IRR) displays the desirability of the investment in each scenario, and a payback time (PB) is calculated to estimate the time required to recover the cost of investment.

To calculate NPV, most authors have applied a 5% discount rate (Liaw & Tsai 2004; Mitchell *et al.* 2005; Rahman *et al.* 2010; Morales-Pinzón *et al.* 2012a), although the CIA World Factbook published a value of 1.75% annualised interest rate (CIA 2012). Given the variety of countries of the different authors we chose to apply a 1.75% discount rate, the specific value for Spain from the CIA publication.

Morales-Pinzón *et al.* (2012a) considered an annual increment of 3% in the price of energy, water, accessories, pumps and workmanship items, and this is similar to the value published by the CIA World Factbook (inflation rate for Spain and Europe is 3.1% per annum) (CIA 2012).

Since we found different views in the literature review regarding the inclusion or exclusion of the inflation rate in these studies, we followed the same methodology for the two options, one including an inflation rate of 3.1% per annum and one excluding it.

Table 4 | Average additive dosage for three levels of water hardness

	Water hardness		
Additive dosage	**Soft**	**Medium**	**Hard**
Detergent	1.00	1.34	1.76
Fabric conditioner	1.00	1.34	1.76
Water softener	0.00	1.00	1.00

RESULTS

The results summarised in Table 5 are grouped by low density and high density scenarios (see Table 1 for details) and by the two options mentioned above: (1) without inflation and (2) considering an inflation rate for Spain and Europe of 3.1% per annum (CIA 2012).

Results show that for low density scenarios and without inflation rate, only LD4 case is feasible with a NPV of €3,767.89 and 21 years PB. When inflation rate of 3.1% is considered, LD4 NPV is higher (€15,578.89) and PB is shorter (15.53 years), also, LD2 is feasible, although less preferable with a very low NPV of €417.64 and a PB of 26 years.

Regarding high density scenarios, in all cases it is possible to obtain the results for the three evaluation criteria. The best choices are HD4 and HD2 that present the most suitable combination of NPV, IRR and PB: for HD4, a NPV of €983,227.00, IRR of 32% and a PB of 3 years, and for HD2, a NPV of €6,498.94, IRR of 37% and a PB of 3 years when considering inflation.

Savings from detergent and softeners seem to have a relevant impact in the financial assessment, showing that with more users (all high density scenarios and LD4), higher NPV values are obtained than those calculated for only one user (one laundry machine) such as LD1, LD2 and LD3.

Table 5 | Financial results

	Without inflation rate			With inflation rate		
	NPV (Euros)	IRR (%)	PB (Years)	NPV (Euros)	IRR (%)	PB (Years)
Low density						
LD1	– 3,186.90			– 3,735.05		
LD2	– 781.32			417.64	2.6	26.27
LD3	– 4,408.08			– 4,147.67		
LD4	3,767.89	3.9	20.92	14,578.89	7.1	15.53
High density						
HD1	37,582.04	22.6	4.40	83,395.62	26.4	4.12
HD2	44,615.14	33.1	3.17	96,498.94	37.3	3.31
HD3	27,163.50	7.1	13.67	75,013.66	10.4	11.59
HD4	450,110.92	28.0	3.53	983,227.00	32.0	3.31

Savings from one user (LD1, LD2 and LD3) during 50 years and including inflation rise to €16,726. The difference between these three scenarios are the costs in the construction and end-of-life stages, due to expensive and greater amounts of material necessary for the storage tank. This is also proven by the fact that even though LD2 and LD3 have no electricity consumption during their use stage, the financial results differ greatly (NPV, IRR and PB).

Moreover, within high density scenarios, we can exclude HD3 as a viable option since its payback period is up to 3.5 times higher than the other three high density scenarios. Savings in HD3 are the same as in scenario HD2 (€193,402 considering inflation and the use of rainwater for laundry during 50 years) since both of them consider 24 users and the cash flows during the stage of use are also equal between them, since neither includes electricity consumption during this stage. Yet HD3 is notoriously more expensive in the first stage (construction) (Figure 3), mainly due to the very high cost and amount of required materials to construct the tank spread on the roof (three times the price of HD1 and HD2). Having more material, the end-of-life stage is also more expensive, 1.75 times the expense of disposal in HD1 and HD2.

Figure 3 illustrates the extent of all expenses (by life cycle stages) and savings during the 50 years of life of the system, considering an inflation rate of 3.1%. It has only

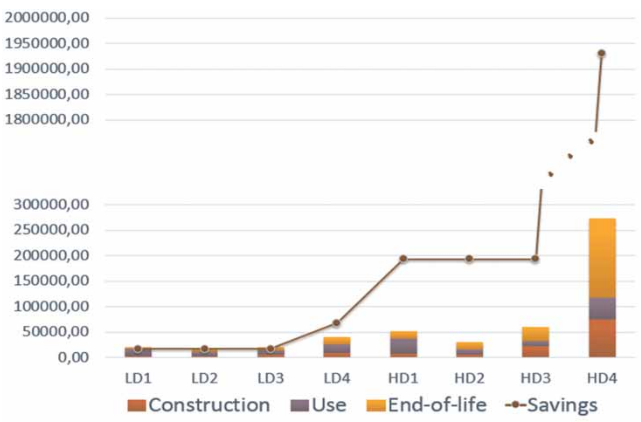

Figure 3 | Outflows (construction, use and end-of-life) and inflows (savings).

demonstrative purpose since it does not reflect the financial behaviour of scenarios, although it does help to identify differences between them.

Although the three first scenarios of each density (LD1, LD2 and LD3; and HD1, HD2 and HD3) contemplate the same amount of users and therefore equal savings, the expenses are different for each, depending on the storage tank configuration. Scenarios HD1 and HD2 have the same amount of users but not the same financial results. HD2 has the best outcomes because: (1) the cost of installing the system is cheaper when the tank is prefabricated and located below roof instead of underground; and (2) there is no pumping and therefore no electricity consumption since gravity works by itself and is free.

CONCLUSION, LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

Within this study, three main contributions to knowledge have been reached: (1) costs and savings have been calculated with the utmost precision; (2) the end-of-life stage has not been previously considered in similar studies, and this innovation brings a consistency to the results of the life cycle perspective; and (3) the inflation rate, which all previous work has taken for granted, without any justification. Associated with this, we adopted two different alternatives: one justified by the CIA World Factbook and a second with no inflation rate.

Results show that high density scenario HD4 is our best choice to achieve higher contributions in a short period of time. Although, if we were limited to only the low density scenario, LD4 would be the only alternative; nevertheless, 16 or 20 years until PB (with and without inflation, respectively) is not affordable for many investors. However, the extent of this advantage is sensitive to the inflation rate.

According to these results, we can conclude that from a financial point of view the recommended scenarios are those of high density, mainly because they have more washing machines, i.e., higher savings from detergent and softener consumption.

Inflation rate has a relevant role in the financial assessment of the investment projects studied. Different entities offer different forecasts regarding inflation rate. These forecasts should be studied and applied to the financial appraisal in order to obtain more accurate results before investment. Without considering inflation, results are less desirable than the values obtained considering a 3.1% inflation rate, and this gives us an idea of what would happen if in a long-term period, such as 50 years, the inflation rate changed.

During this study, a limitation was found: the savings on the water bill from no tap water consumption (when replacing it by rainwater) were not included.

Future research should consider several factors in order to extend this study: (1) the effect of no tap water consumption on the water bill, and include these possible savings in the financial analysis; (2) the effect of climate change in pluviometry, since this would impact greatly on savings; (3) water price forecasts; and (4) water hardness deteriorating effect on washing machines and their renewal or replacement costs.

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