View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Diposit Digital de Documents de la UAB

This is a post-peer-review, pre-copyedit version of an article published in The International Journal of Life Cycle Assessment. Vargas-Parra, M. V., Rovira-Val, M. R., Gabarrell, X., & Villalba, G. (2018). Rainwater harvesting systems reduce detergent use. *The International Journal of Life Cycle Assessment*, 1-15. The final authenticated version is available online at: http://dx.doi.org/10.1007/s11367-018-1535-8.

Rainwater harvesting systems reduce detergent use

M. Violeta Vargas-Parra. [1, 2], M. Rosa Rovira-Val[2, 4], Xavier Gabarrell*[2, 3], Gara Villalba[2, 3].

1. Department of Civil and Environmental Engineering, Technical University of Catalonia–Barcelona Tech (UPC, Campus Nord), C/Jordi Girona 1-3, Building C1, 08034 Barcelona, Spain
2. Sostenipra (ICTA, 2017 SGR 1683) Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB), Campus Bellaterra, 08193 Cerdanyola del Vallès, Spain. María de Maeztu Center.
3. Department of Chemical, Biological and Environmental Engineering, Biotechnology Reference Network (XRB), School of Engineering, Universitat Autònoma de Barcelona (UAB), Campus Bellaterra, 08193 Cerdanyola del Vallès, Spain.
4. Department of Business Economy, Universitat Autònoma de Barcelona (UAB), Campus Bellaterra, 08193 Cerdanyola del Vallès, Spain.

*Corresponding author. Xavier.Gabarrell@uab.cat; phone: (+34) 93 586 8778. Fax: (+34) 93 581 3331.

Abstract

Purpose: Due to population growth, urban water demand is expected to increase significantly, as well as the environmental and economic costs required to supply it. Rainwater harvesting (RWH) systems can play a key role in helping cities meet part of their water demand as an alternative to conventional water abstraction and treatment. This paper presents an environmental and economic analysis of RWH systems providing households with water for laundry purposes in a life cycle thinking perspective.

Methods: Eight urban RWH system scenarios are defined with varying population density and storage tank layout for existing buildings. Storage tank volume required is calculated using Plugrisost software, based on Barcelona rainfall and catchment area, as well as water demand for laundry, since laundry is a fairly constant demand of non-potable water. Life cycle assessment (LCA) and Life cycle costing (LCC) methodologies are applied for this study. Environmental impacts are determined using the ReCiPe 2008 (hierarchical, midpoint) and the cumulative energy demand methods. Net present value (NPV), internal rate of return (IRR) and payback time (PB) were used in LCC. Savings from laundry additives due to the difference in water hardness was, for the first time, included in a RWH study.

Results and discussion: LCA results indicate that the best scenario consists of a 24-household building, with the tank spread on the roof providing up to 96% lower impacts than the rest of scenarios considered. These results are mainly due to the absence of pumping energy consumption and greater rainwater collection per cubic meter of built tank capacity. Furthermore, avoided environmental impacts from the reduction in detergent use are more than 20 times greater than the impacts generated by the RWH system. LCC indicates that RWH system in clusters of buildings or home apartments offer up to sixteen times higher profits (higher NPV, higher IRR and lower PB periods) than individual installations.

Conclusions: LCA and LCC, present better results for high density scenarios. Overall, avoided environmental and economic impacts from detergent reduction clearly surpass environmental impacts (in all categories except terrestrial acidification) and economic cost of the RWH system in most cases (except two scenarios). Another important finding is that 80% of the savings are achieved by minimizing detergent and fabric softener by using soft rainwater; and the remaining 20% comes from replacing the use of tap water.

Keywords: Financial analysis; laundry additives; rainwater; hardware; urban planning; urban sustainability; industrial ecology; LCA; LCC.

Acknowledgements: The authors would like to thank the project "Análisis ambiental del aprovechamiento de aguas pluviales" (Spanish Ministry for Science and Innovation, ref. CTM 2010-17365) for financing this study and express appreciation for the grant awarded to M. Violeta Vargas-Parra by Conacyt (National Council of Science and Technology, decentralized public agency of Mexico's federal government). The authors also acknowledge the financial support from the Spanish Ministry of Economy and Competitiveness, through the "María de Maeztu" program for Units of Excellence in R&D (MDM-2015-0552), ICTA Unit of Excellence. Special thanks to Michaël Grelaud and Rainer Zahn for their help understanding and calculating climate change precipitation forecasts and to Jeroen Van Den Bergh for his ongoing suggestions and valuable inputs to this research.

Introduction

Water has limited availability although it is a renewable resource. Less than one percent of fresh water resources is usable for ecosystems and human consumption (World Water Assessment Programme (WWAP) 2006; United Nations Environment Programme (UNEP) 2007). During the XX century, global water consumption has increased at twice the rate of population growth (Food and Agriculture Organization of the United Nations (FAO) 2012). Moreover, "water stress" (European Environment Agency 2014) will be further intensified due to climate change. For example, precipitation of the Mediterranean area of southern Europe is expected to decrease 5% by 2020 in comparison with the climatology of 1979-2001 (Met Office Hadley Centre for Climate Change 2009). Accordingly, higher water supply vulnerability is expected in urban areas (The World Bank 2009; Leflaive 2012; World Water Assessment Programme (WWAP) 2012).

Water resource management is an essential component for the sustained development of society and economy (United Nations Development Programme 2006) and the unsustainable exploitation of this resource represents an increasing threat for human development (World Water Assessment Programme (WWAP) 2009). Furthermore, water depends on energy for treatment and distribution, and energy depends on water in all phases of energy production and electricity generation (also known as the water-energy nexus) that further accentuates the need for a more sustainable water management.

Rainwater harvesting (RWH) could potentially meet part of the city's water demand in a cost-effective way while reducing environmental impacts. Moreover, Fragkou et al. (2015) determined that the Mediterranean region has a significant potential to supply its water needs from rainwater runoff, considering all urbanized areas as collectors, the water self-sufficiency potential ranges from 8% to 500%, with an overall average above 100% for the regional system. Other authors like Abdulla and Al-Shareef (2009); Angrill et al. (2011); Rahman et al. (2014) have also seen rainwater as an optimal alternative source of water in urban areas, although their focus is on either, a specific use, or to fulfill water demand from a variety of sources, including tap water and rainwater among them.

Rainwater contains a low concentration of minerals, such as calcium and magnesium, which makes it highly attractive for regions with hard water supply where water hardness results in pipe clogging and consequently elevated maintenance costs. In the households, it is estimated that hard water can increase appliance maintenance cost by as much as 30% (WQA 2010). Another negative effect of hard water which is often overlooked is its direct relation to detergent use. According to detergent manufacturers, the dosage of detergent needed for washing a load of laundry with hard water can be as much as 1.59 times greater than using softer water according to label instructions of 10 laundry detergents and 10 fabric softeners. Moreover, energy intensity of laundry can be also reduced, surfactants present in detergents better perform with warm water, especially when hard water is supplied. In comparison with other potential non-potable uses, laundry is the one that consumes more energy during its use. Specifically compared with toilet flushing, pumping energy needs

are the same, although laundry per-se includes extra energy consumption from washing machines. In the case of garden watering, energy needs tend to be lower since gardens are usually at ground level.

Such as is the case for the Metropolitan Area of Barcelona, which receives its water from limestone river basins resulting in a water hardness of 315 mg $CaCO_3$/l. Rainwater can be used as an alternative source of soft water for laundry and not only alleviate primary sources pressure on water supply but also save environmental and economic cost for conscientized families, assuming that the decision of installing a RWH system is due to a social awareness mainly on environmental aspects and a willingness to a change of habits in pursue of more environmentally friendly alternatives.

Several studies have determined additional advantages for RWH for the Metropolitan Area of Barcelona. Angrill et al. (2017) concluded that harvested rainwater has better physicochemical properties than tap water. In an earlier life cycle analysis, Angrill concluded that a RWH gravity system for laundry purposes in a compact distribution in newly constructed residential areas with the right distribution strategy can reduce 67% of the CO_2 emissions (0.64 CO_2eq/m^3) in comparison to desalination (1.96 CO_2eq/m^3) or 57% less when compared to water transfer from a river (1.51 CO_2eq/m^3).

In another study by Farreny, the cost-efficiency of RWH systems was evaluated in a dense neighborhood in a city near Barcelona concluding that RWH systems should be installed at the neighborhood level considering 43 multi-story buildings (a total of 558 dwellings), since it enables economies of scale (Farreny et al. 2011). In Greater Sydney, Australia, (Rahman et al. 2012) financial viability was explored for single-family detached homes through a water balance simulation model, finding that benefit cost ratios for rainwater tanks of $2m^3$, $3m^3$ and $5m^3$were smaller than 1.00 without government rebate. From a resource accounting perspective Vargas-Parra et al., 2013 found that the scenario with the lower resource (material and energy) consumption, using Exergy analysis, was a building of 24 home-apartments with the tank installed on the roof. And that, in general, scenarios with more users (24 home-apartments or 240 home-apartments) consume 3-5 times less resources per cubic meter than those scenarios considering a single-family user.

Most of these studies lack a complete vision of the use stage by failing to consider some of the advantages of using rainwater instead of tap water such as the savings on detergent. Furthermore, previous authors do not provide an integrated environmental and economic assessment in order to optimize both cost and environmental burden, likewise, recent studies conclude that RWH systems implementation and the selection of the technology are strongly influenced by economic constraints (Campisano et al. 2017). Moreover, even though, Farreny et al. 2011a; Imteaz et al. 2011; Angrill et al. 2011; Rahman et al. 2012; Vargas-Parra et al. 2013 and Morales-Pinzón et al. 2015 studied urban RWH systems for laundry purposes (among others) none of these studies included the savings from detergent, not from an environmental point of view nor from the economic point of view.

Additionally, previous studies are too city-specific and not transferable or applicable to other urban areas. This work aims to fill this research gap by performing a Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) of a RWH system as an alternative supply of domestic laundry water based on eight scenarios varying in population density and tank location. The metropolitan area of Barcelona serves as the case study for the analysis, illustrating the applicability of the method to urban systems. Results are applicable to all urban areas with high water hardness levels and the concepts are generalizable to any case study.

The Rainwater Harvesting System

Urban areas are understood as territorial units with a large number of inhabitants living mostly in built-up areas which may include villages and towns in rural districts (Eurostat 2013). European Union (EU) regions population density ranges from 21,464 inhabitants/km^2 (Paris, France in 2011) to 10 inhabitants/km^2 (Soria, Spain in 2011) (Eurostat 2014) and within regions and cities, population density can also vary amongst

neighborhoods, i.e. in Paris, the eleventh arrondisement doubles the density of the city with almost 42,000 inhabitants/km^2 (INSEE 2013) and in Barcelona seven neighborhoods exceed 100,000 net inhabitants/km^2 (Barcelona City 2015). To represent urban areas, two densities are proposed: 1) low density of 10 inh/km^2 (LD) and 2) high density of 63,600 inh/km^2 (HD). The LD considers a single-family home with a 250 m^2 rooftop which serves as the catchment area. The HD considers a five-story building with 24 home-apartments with 700 m^2 of catchment area. For each density, we consider several scenarios, which vary in the location of the storage, as shown in figures 1a, 1b and 1c the storage tank can be installed underground (Figure 1a), below the roof (Figure 1b) or spread on the roof (Figure 1c) (profile diagram provided in supplementary information Table S3). A fourth scenario of a cluster is included in each density: For LD considers a cluster of four LD houses with the tank installed underground, and similarly, for HD, a cluster of ten HD buildings with the tank installed underground is considered. These cluster scenarios have a larger catchment area and consequently greater rainwater collection.

<Figure 1>

Table 1 summarizes the eight different scenarios, showing the two densities, storage size and location, and the relation between the provided rainwater and the laundry needs of each household, in which laundry demand was calculated as five laundry loads per week and a water consumption of 96 liters per load for each household considering an eco-labeled washing machine according to the European Commission Decision 2000/45/EC (European Commission 2007).

<Table 1>

Barcelona average annual rainfall is 640 mm ranging from less than 20mm to 90 mm per month, therefore, potential rainwater supply and storage tank size were calculated using Plugrisost®, a free simulation model developed by Gabarrell et al. (2014), which evaluates the RWH potential and environmental impact of different water supply alternatives for urban use. The model estimates the potential rainwater supply based on historical daily rainfall statistics from 1991 to 2010 for Barcelona (Catalonia Meteorological Service (SMC) 2011), a roof-runoff coefficient of 0.9, and the catchment area defined in Table 1 for each scenario. Storage tank sizing calculations are a function of water demand of 25 m^3 per year per household. Results from the Plugrisost software are consistent with other studies, such as Campisano and Modica (2012) and Imteaz et al. (2013).

Methodology (LCA and LCC)

A life cycle approach was followed for both environmental and economic analyses. Life Cycle Assessment was applied to calculate the environmental burdens and Life Cycle Costing to assess the economic performance of RWH systems in urban areas.

1.1 LCA

The LCA methodology used is the ISO 14040 (ISO 2006), and life cycle impact assessment (LCIA) results are calculated at midpoint level using ReCiPe (Goedkoop et al. 2013) and cumulative energy demand methods for each life cycle stage for selected impact categories Climate Change (CC; kg CO_2 eq), Ozone Depletion (OD; kg CFC-11 eq), Terrestrial Acidification (TA; kg SO_2 eq), Freshwater Eutrophication (FE; kg P eq), Photochemical Oxidant Formation (POF; kg NMVOC), Particulate Matter Formation (PMF; kg PM10 eq) based on the ReCiPe hierarchical midpoint characterization approach and the single method Cumulative Energy Demand (CED; MJ).

1.2 LCC

The economic analysis is based on the LCC methodology as described by ISO 15686-5 (ISO 2008) according to which, different financial techniques or indicators may be used in LCC (ISO 2008) depending on the

requirements of the investors. Net Present Value (NPV) is considered a standard criterion to decide if an option can be justified on economic principles.

NPV (Euros) is the sum of the discounted future cash flows, defined as the difference between the present value of inflows and outflows and determines the current value of the initial investment and all future incomes/outcomes over the 50 years of lifespan of the system (Eq. (1)).

$$NPV = -I + \sum_{i=0}^{T} \frac{C_i}{(1+r)^i} \quad (1)$$

Where:

$I =$ Initial cost or initial investment.

$C_i =$Cash flow at year *i*. (cash inflows minus cash outflows at year *i*. Inflation rate of 3% (IMF 2012))

$r =$ Discount rate (4% (Banco de España 2013).

$p =$The value of discounted cash flow at which the first positive value of discounted cumulative cash flow occurs.

$n =$The value of discounted cash flow at which the last negative value of discounted cumulative cash flow occurs.

$y_i =$The number of years after the initial investment at which last negative value of discounted cumulative cash flow occurs.

Cumulative cash flow$= \sum_i^T C_i$

The internal rate of return (IRR, %) is also determined, and it appraises how financially attractive the investment of each scenario is by indicating the rate at which NPV becomes zero as is expressed by equation 2.

$$NPV = \sum_{i=0}^{I} \frac{C_i}{(1+r)^i} = 0 \quad (2)$$

The payback period (PB, years) gives an estimate of the time required to recover the cost of investment. It is calculated based on the number of years elapsed between the initial investment, its subsequent cash outflows and the time at which cumulative cash inflows offset the investment (Eq. (3)).

$$PB = \frac{(p-n)}{p} + y_i \quad (3)$$

1.3 Goal and Scope

The LCA and LCC are based on a cradle-to-grave approach as depicted by Figure 1. The construction stage includes the energy (including transport) and materials required for the extraction, production, manufacture and installation of the RWH system, which can have three different rainwater storage configurations: a) underground, b) top floor but inside the building, and c) the entire roof area.

Also included in the construction stage is the energy and materials for the maintenance of the system during its useful lifetime of 50 years, which is based on the durability of the materials employed and based on previous literature on construction assets which state a general lifespan of 50 to 100 years for construction materials (Frijia et al. 2011; Sandin et al. 2014). Materials and parts with shorter lifetimes require replacements which are also included.

The use stage considers the energy requirements. Also, laundry detergents and other additives savings are considered in this stage for the 50-year period.

At the end of 50 years, the end-of-life (EOL) stage includes the energy and materials required for the dismantling of the system and transport of the materials to a waste management plant. Recycling or final disposal of the used materials is not considered as part of the system under study, because there is uncertainty in the technological advances in 50 years from now. Also, rainwater per se is considered out of the system boundaries of this study, as well as service water or any water treatment after the use of rainwater. It is assumed that rainwater has no environmental burdens or cost for the system and treatment of service water or waste water is part of the succeeding life cycle as input.

As illustrated by Figure 1, domestic RWH systems are commonly composed of three main parts, namely: a catchment area, which is placed on the rooftop for all cases considered in this study; a storage facility (it can be installed underground or aboveground); and a delivery system to transport the rainwater from the catchment area to the storage facility and also from the storage facility to the building, and in this case, directly to the laundry machine within the building.

Wastewater and wastewater treatment are excluded from the system assuming that water consumption maintains the same total quantity as if it was supplied only from tap water, and therefore, same amount of wastewater. Wastewater treatment was left out of the system boundaries because, although it is assumed that rain-wastewater from laundry will have less detergent (phosphates) this will not make a difference on a city level treatment plant.

The functional unit is defined as 1 m^3 of rainwater supplied for domestic laundry purposes. Since NPV, IRR and PB are project-oriented financial tools, these were first calculated based on the construction, use and dismantling of a RWH system as a unit. Subsequently, results were divided by the amount of water supplied, in order to obtain the same functional unit: 1 m^3

1.4 Life Cycle Inventory

Inventory data and economic cost were obtained from several sources. Material and energy requirements for each life cycle stage were gathered from the publicly available data from the project PLUVISOST funded by the Spanish Ministry of Science and Innovation (Angrill et al. 2011) which analyzed the environmental consequences of urban rainwater harvesting. Material and processes life cycle were selected from Ecoinvent 3 database. Table 2 presents the input data per functional unit considered in the environmental assessment.

<Table 2>

Data on cost of materials, labor, tools and equipment were obtained from three different sources: (i) The Technology of Construction of Catalonia Institute database (ITeC 2012), (ii) the Guadalajara's mid-level Architecture official college database (Colegio Oficial de Aparejadores 2012) and (iii) internet catalogues were consulted for tank and pump prices (Aguadelluvia 2012; Baeza Group 2012; Ebara 2012; Graf Ibérica 2012; Hasa 2012; Remosa 2012; Saci 2012). Furthermore, the costs were validated by a senior professional of water installations in Barcelona. Table 3 shows the description and general cost of the items considered in each life cycle stage: construction, use, and EOL. Table S1 in the supporting information contains the inventory of all costs considered for each scenario.

<Table 3>

a. **Construction stage**

Construction stage includes materials, energy and labor consumption associated with the construction, installation, maintenance and replacement associated with the operation of the RWH system during its lifespan in Barcelona. Construction services include manpower for excavation, installation and dirt transportation, energy consumed by construction machinery is accounted as fuel (diesel). Construction materials include: Recycled wood formwork, concrete CEM II/A-L 32.5R, steel frame, waterproofing sheet, bricks and mortar lining for the construction of the storage tank, polypropylene for piping, and stainless steel as main component

for pumps and filters. Finally, in the construction stage inventory, transport of materials from the producer to the site of construction, estimated as 50 km. Replacements are included in this stage, even though, materials are consumed after construction.

Also included in this stage is the equipment and material replacements necessary to keep the system in proper operating conditions, i.e. replacement of the pumps and filters every ten and five years respectively, as well as the labor costs associated to these activities.

b. **Use stage**

This stage includes the electricity for pumping water on a yearly basis (necessary for scenarios where the tank is installed underground), calculated as the energy requirements (kWh/m^3) multiplied by the amount of rainwater supplied in each scenario.

During the use stage, two different aspects are considered in the calculation of savings. First, using soft rain water reduces the amount of detergent, fabric softeners, and de-calcifying additives, thereby reducing the cost of doing laundry by 62%. Based on the prices of more than ten brands of laundry products available in supermarkets in Barcelona in 2015, we calculated the following averages for a dose of 65 ml: detergents 0.24 euros per dose, fabric softeners 0.06 euros per dose and water softeners 0.42 euros per dose. The second aspect contributing to the savings is the reduction in tap water consumption for laundry. The average cost of tap water in Spain in 2014 was 1.7 Euros/m^3 (RTVE 2014) .

Annual water demand for laundry was calculated as 25 m^3 per household, considering an average of 96 liters per washing cycle (Wastewater Gardens International 2010) and 250 cycles. The doses of additives are those recommended by the manufacturer for the different ranges of water hardness. Barcelona's tap water is considered hard, (315 ppm) and the doses are 1.59 detergent, 1 water softener, and 1.59 fabric softener. On average, manufacturers consider one dose as 65 ml, and the recommendation for soft water is one dose of detergent and one of fabric softener per laundry load (water softener is not necessary).

Cost and environmental burden of using other sources of water such as tap water to fulfil laundry water demand were not taken into account, although, intrinsically they are included. The system has been designed specifically for that amount that can be supplied, all costs and burdens of a RWH system are taken into account and savings too. And, therefore, savings are only accounted for that system and that amount of rainwater and there are no savings or burdens from other systems such as tap water supply or wastewater treatment.

c. **End-of-life**

The costs associated with the dismantling of the facilities are taken into account, including the transportation costs as well as the labor necessary for excavation and dismantling and energy consumed by machinery (as fuel). The deconstructed materials (rubble) are sent to a waste management plant located at a maximum distance of 50 km from where it was installed.

An examination of all the costs associated with the suitable performance of the facilities during their lifetime was considered (Table 3).

1.5 Sensitivity Analysis

Material and labor cost were considered as high quality data with a low degree of uncertainty since two data sources were used and were validated by field experts. Discount rate published by the National Bank of Spain was deemed of high quality and certainty. Likewise, water hardness was taken as a fixed data. However, inflation rate, precipitation and tap water price may vary over time and cause uncertainty in the results. The cumulative effect of inflation rate can play an important role in the costs of the RWH system and thus a sensitivity analysis was performed to quantify to what extent changes in inflation rate can alter NPV, IRR and

PB. Secondly, a sensitivity analysis is performed evaluating the precipitation forecasts affected by climate change for the Mediterranean area based on two scenarios defined by IPPC (IPCC 2000). Finally, a third sensitivity analysis was carried out to evaluate the effect of an increase in tap water price reflected directly in the savings from no tap water consumption.

Inflation sensitivity analysis.

Due to uncertainty in inflation rates, LCC studies can be based on actual market price instead of selecting an inflation value, see for example Cellura, Ardente, & Longo, 2012; Debacker, Allacker, Spirinckx, Geerken, & De Troyer, 2013; Peri, Traverso, Finkbeiner, & Rizzo, 2012; and Wong, Tay, Wong, Ong, & Sia, 2003. In order to be representative of these options, the sensitivity analysis is based on two alternatives:

- Alternative 1: IMF forecasts for the next five years (until 2020) and after that a constant inflation rate equal to the value of 2020, that is: -0.73% for 2015, 0.68% for 2016, 0.81% for 2017, 1.15% for 2018, 1.32% for 2019 and 1.51% for 2020.
- Alternative 2: No assumptions made; instead, all calculations are based only on the current market price (neglecting time value of money).

For both alternatives, a discount rate of 0.75% published by the National Bank of Spain is applied (Banco de España 2013).

Precipitation sensitivity analysis.

It is important to establish how sensitive the economic analysis is to varying precipitation patterns given the negative influence of climate change (Solomon et al. 2007). Based on historical precipitation data (1991-2010), precipitation has decreased about 1% every year, resulting in a 19% decrease over the 20 years. Figure S1 shows the precipitation of 20-year historical data (1991-2010), presented yearly and monthly specifically to demonstrate the tendency of the data. The sensitivity analysis is based on the following alternatives:

- Alternative 1 considers that this tendency of 1% yearly decrease is continued for the next 50 years.
- Alternatives 2 and 3 are based on the report made by the Meteorology Service of Catalonia (SMC) (Barrera-Escoda and Cunillera 2011), where two climate change scenarios are considered for Catalonia region based on scenarios A2 and B1 proposed on IPCC 2000. A2 is a regionally oriented economic development scenario, with a decreasing precipitation trend of 8% for 2011-2040 and 8% for 2041-2070. B1 is based on a trend towards global environmental sustainability resulting in a decreasing precipitation rate of 1.4% for 2011-2040 and 3.8% for 2041-2070. Table of the results is given as supporting information in Table S5.

Tap water price sensitivity analysis.

As water scarcity and shortage become an issue, costly mechanisms (i.e. desalination, inter-basin transfers, others) are emerging to help allocate water more efficiently. Statistical evidence shows that water price tends to increase, reflecting the growing scarcity of water supplies (Maxwell 2010). Based on water prices report from the Catalan Water Agency (Agència Catalana de l'Aigua), water price has increased 50% over the last 10 years, resulting in a mean yearly increment of 5%. Figure S2 shows the water price evolution of the past 10 years (2005-2015), presenting the yearly price and increment in relation to the year before. The sensitivity analysis is based on this past increment of 5% in the water price annually and it is applied for the next years.

Results

1.6 Environmental Impacts

Firstly, the environmental analysis results without considering avoided impacts are presented in Figure 2 for all eight scenarios for the selected impact categories.

<Figure 2>

The best environmental performer is scenario HD3 for all impact categories except for OD, due to the use of a waterproofing foil which requires Polyvinylchloride (PVC), entailing a substantial amount of chlorinated alkenes waste during the PVC's production phase, see Table S2 in supporting information. HD3 performs better than all other scenarios because it requires less materials per cubic meter of harvested rainwater taking advantage of the already built surface and gravity to supply rainwater

Within low density scenarios, LD1 is the best option, mainly because it has a smaller storage tank (5 m3) than most other scenarios (LD3 has $9m^3$ capacity due to the design spread over the roof that includes a dead space and LD4 with a 209 m^3 storage volume) resulting in less material and energy required for production, installation, and end-of-life-disposal.

The highest impacts within the low density scenarios are given by scenario LD3 for five out of the seven categories (CC, OD, TA, POF and PMF). This is because this scenario requires reinforcement materials and waterproofing materials to have the tank spread on the roof. On the other hand, for high density scenarios, the least favorable scenario is HD1 mostly due to energy consumption during the use stage for pumping water to the top of a five-story building.

Table S2 in supporting information shows all environmental impact results for the eight scenarios by life cycle stage, here we concentrate on the climate change impact category because is as the operative metric under the UNFCCC and Kyoto protocol has made it the metric of reference.

Figure 3 represents the contribution of each life cycle stage in climate change impact category for all eight scenarios. In scenarios LD3 and HD3 construction stage is responsible for more than 80% of the total impact and this is due to construction materials, specifically the waterproofing sheet needed to protect the ceiling concrete structure, that contains PVC and fiberglass (both materials have high environmental costs). The difference between these two scenarios is the volume of water that can be collected in each. HD3 requires double the amount of waterproofing sheet than LD3, but is able to collect more than ten times more rainwater, resulting in lower impacts per functional unit (cubic meter).

Furthermore, worst low density scenario (LD3) is affected by the production stage, particularly by the waterproofing sheet used for the storage tank that in this scenario is spread on the roof. Then, for the best low density scenario (LD1), even though production stage still is 80% of the total CC impact, the impact in all categories for this scenario is about half of those on LD3 and up to 30% of the other two low density scenarios, this is because the tank is smaller in LD1 than the other low density scenarios, it does not use the waterproofing sheet and the energy for pumping rainwater is not as high as in LD4, because in LD1 rainwater only has to travel vertically from the storage tank to the washing machine above it and in LD4, rainwater has to travel across the backyard from the shared storage tank to one of the houses and then vertically from the storage tank's depth to the washing machine at street level.

<Figure 3>

In high density scenarios, worst environmental outcome for most of the categories is given by scenario HD1, except for categories OD and CED, this is mainly due to impacts related to energy consumption during the stage of use where electricity is required for pumping. As can be seen in Figure 3, approximately 60% of the total CC impact is given by the stage of use.

1.7 Avoided impacts

As a result of the difference in water hardness between Barcelona's tap water and rainwater, the consumption of laundry detergent and other additives can be reduced 62%. In this section, environmental impacts avoided by the reduction in laundry detergent consumption are assessed.

Inventory data was obtained from P&G detergent (Saouter and Hoof 2002). Input data per cubic meter of water for laundry purposes is available in Supporting Information Table S3.

Each load of laundry consumes around 96 liters of water. According to average manufacturer instructions (on the labels of products) on detergent dosage, soft (rain) water requires one dose per load, whereas hard water requires 1.59 doses.

Table 4 presents the environmental impacts that were avoided when using rainwater instead of Barcelona's tap water. Since the avoided impact is given per cubic meter of water for laundry, the avoided impact of each scenario depends on the use of water. Subtracting these impacts from the environmental impacts of the RWH system, environmental impacts are significantly reduced. In the best case scenario, impacts are reduced more than two times (HD3) in all impact categories.

<Table 4>

1.8 Life cycle cost results

Results are grouped in Table 5 by Low density (LD) and High density (HD) scenarios, further disaggregated by position of storage area and also by single construction or a cluster construction according to the scenarios summarized in Table 1. Results show that all HD scenarios (single and cluster construction) are economically feasible and result in positive Net Present Value (NPV). With initial investments ranging from less than 3,500 euros for scenarios LD1 and LD2, less than 10,000 euros for LD3, LD4, HD1 and HD2, 23,000 euros for HD3 and less than 75,000 euros for HD4 and this gives us initial investments of 3,600 euros in average per family in LD scenarios and an average of 470 euros per family in HD scenarios The HD scenarios also have higher Internal Rate of Return (IRR) than all LD scenarios and have a payback period (PB) of less than 3 years, except for the single building HD scenario with roof storage (HD3), which is 10.4 years. High density cluster scenario (HD4) is the best overall performer because it offers the highest NPV, a high IRR and the shortest PB.

For Low density scenarios, only LD2 and LD4 have positive NPVs. However, results show elevated PB of 17 and 12 years, resulting less desirable investment projects than HD but still viable options. Contrary to this, LD1 and LD3 with negative NPV are not viable.

<Table 5>

The cluster construction scenarios for both low and high density (LD4 and HD4) have the highest cumulative cash flows as illustrated by Figure 4. This is due to the fact that the costs associated with the construction and use phase for single building scenarios, are higher (on a per-m^3 basis) than for the cluster scenarios. For example, the cost of waterproofing materials in scenarios LD3 and HD3 is highly expensive, causing NPV to decrease up to 130% in regard to scenario LD4. Scenarios where the tank is installed underground (LD1 and HD1) result in high costs related to the electricity required for pumping and the replacement and maintenance of the pump, decreasing cumulative cash flows in an average of 80% compared to scenarios with the same amount of users and savings, as LD2 and HD2. Figure 4 also shows how cluster scenarios compensate initial investment faster and with higher cumulative cash flows at the end of the study even after having a slight decrease due to the dismantling costs.

<Figure 4>

Moreover, 80% of the savings are achieved by minimizing, from 1.59 doses to 1 dose per laundry, the consumption of detergent, fabric conditioner and water softener, and the remaining 20% comes from replacing the tap water consumption for laundry purposes.

The life cycle approach taken by this study is especially useful in quantifying the contribution of costs and savings during the entire lifetime of the infrastructure. This is illustrated by Figure 5 for the cluster scenarios which were the best performers in terms of the financial indicators discussed above. During use stage, costs due to electricity barely affect the high density scenario as compared to low density scenario because yearly savings represent about 10% of initial investment in low density LD4 and almost 40% for high density HD4 initial investment; therefore, initial investment is recovered easily within a few years in HD4.

<Figure 5>

1.9 Sensitivity Analysis

As mentioned above, three variables; inflation rate, precipitation and tap water price, may vary over time and cause uncertainty, therefore, three sensitivity analysis were performed in order to analyze the effect of them in our study.

Inflation sensitivity analysis.

Inflation rate is variable over time and space; two alternatives are assessed:

- Alternative 1: IMF forecasts for the next five years (until 2020) and after that a constant inflation rate equal to the value of 2020, that is: -0.73% for 2015, 0.68% for 2016, 0.81% for 2017, 1.15% for 2018, 1.32% for 2019 and 1.51% for 2020.
- Alternative 2: No assumptions made; instead, all calculations are based only on the current market price (neglecting time value of money).

For both alternatives, a discount rate of 0.75% published by the National Bank of Spain is applied (Banco de España 2013). Based on the formula and its application, considering that NPV and IRR are directly proportional to the inflation rate. Thus a higher inflation rate results in higher profits and higher rate of return. Consequently, the lowest NPV and IRR values are given when no inflation rate is considered. This proves that the inflation rate value is significant and should be included in feasibility studies since this could affect the profitability of the project and the investor's decision process. Results of the inflation sensitivity analysis are given in the supporting information (Table S4) where it becomes evident that inflation makes a big impact in financial results, more specifically in the case of HD4, showing differences of around 20 to 50 percent in NPV values and from 5 to 10 percent in IRR results. For PB the differences are less than 1%. On all cases higher on alternative 1 (higher inflation rate) and lower on alternative 2 (no inflation rate), and the lowest of all is base scenario, showing that even when inflation is negative, HD scenarios are all feasible.

Precipitation sensitivity analysis.

Precipitation patterns have been changing over time and with the negative influence of greenhouse gas concentration, patterns may vary more drastically and the RWH system depends on it. Sensitivity analysis is based on the following alternatives:

- Alternative 1 considers that this tendency of 1% yearly decrease is continued for the next 50 years.
- Alternatives 2 and 3 are based on the report made by the Meteorology Service of Catalonia (SMC) (Barrera-Escoda and Cunillera 2011), where two climate change scenarios are considered for Catalonia region based on scenarios A2 and B1 proposed on IPCC 2000. A2 is a regionally oriented economic development scenario, with a decreasing precipitation trend of 8% for 2011-2040 and 8% for 2041-2070. B1 is based on a trend towards global environmental sustainability resulting in a decreasing

precipitation rate of 1.4% for 2011-2040 and 3.8% for 2041-2070. Table of the results is given as supporting information in Table S5.

When changes in precipitation due to the climate change effect are included in the financial calculations, there are no significant changes in NPV, IRR and PB. The highest differences are given in scenarios HD1, HD2 and HD3 when alternative 1 is considered, resulting in a maximum of a 30% reduction of the NPV, a maximum reduction of 10% of the IRR and an increase in PB of 8 months maximum. Moreover, taking into account the typical irregular rainfall in Mediterranean areas where annual rainfall is low, with more than half falling during the winter, this analysis, not only proves that this is not an input of uncertainty to our study, but it also proves that even when precipitation tends to diminish, RWH will continue to be an advantageous supply of water for laundry in economic terms.

Even though our analysis only includes the economic performance changes, reliability on rainwater supply on LD scenarios is considered to be maintained, considering that LD scenarios were already only using 50% of the capacity. For LD scenarios, is the best way to adapt to climate change. For HD scenarios reliability may have decreased and a revision and recalculation at 10 or 25 years would be recommended and at this point all costs (economic and environmental) would be depreciated, and a new investment may be feasible. Although studies on climate change effect on rainwater harvesting are limited, results are in accordance with recent studies, such as Haque et al. 2016; Kisakye et al. 2018 on the effect of climate change on rainwater harvesting around the world.

Tap water price sensitivity analysis.

Based on water prices report from the Catalan Water Agency (Agència Catalana de l'Aigua), water price has increased more than 50% over the last 10 years. The statistical relationship obtained through linear regression resulted in an increase of 5% annually. Figure S2 shows the water price evolution for the past 10 years (2005-2015), presenting the yearly price and increment in relation to the year before. The sensitivity analysis is based on this past increment of 5% in the water price annually and it is applied for the next years.

Savings from no tap-water consumption have a great effect in financial outcomes. Alternative scenario presents an increase of up to 30% in LD scenarios and up to 45% in HD scenarios. Results from the water price sensitivity analysis are given in Table S6.

An increase in tap water price affects the profitability of the project and does not affect the environmental aspects.

Discussion

The environmental assessment helps to point out the high impacts associated with the production stage, more specifically to the materials and energy needed to install the tank. Even though scenario HD2 has no pumping energy requirements, the fact that it uses more reinforcement materials results in higher impacts than scenario HD3. In the case of low density scenarios, saving energy from pumping is not always the best option, reinforcement materials in the case of scenario LD2 and waterproofing foil in scenario LD3 have a negative effect even though these scenarios use gravity to supply water.

The high density scenario HD3, made up of one building and 24 households with the tank spread on the roof has the lowest environmental impacts in most categories, except for Ozone Depletion (OD; kg CFC-11 eq). HD3 collects 283 m^3 per year and has no pumping needs nor structural reinforcement. Even though high density scenarios can only provide 50% of the laundry water demand, they collect a higher amount of rainwater than those in low density and have in general lower environmental impacts, because all the water is consumed, a higher demand allows more benefit. In addition to this, avoided detergent due to the substitution of hard tap

water with soft (rain) water in domestic laundry, results in reducing environmental impacts of the rainwater harvested (per m^3) by the RWH system in half for most scenarios.

Similar to the environmental results, the economic analysis leads us to conclude that a RWH system is economically feasible for domestic laundry use for the types of residences considered in this study. The high density cluster construction configuration (HD4), which consisted of ten buildings and 240 households with the tank installed underground, had the best overall results. Financial results present the highest NPV of 753,896 euros, an IRR of 38% and a PB of 2.6 years. The high density construction scenarios have better outcomes because they require a lower rate of initial investment per m^3 of water and also because the high expenses of the construction stage are compensated by the savings resulting from less detergent use. 80% of the savings are attained due to the reduction in laundry detergent consumption.

The location of the storage facility plays an important role in both, the economic and the environmental analysis. In low density scenario LD3 and high density scenario HD3, where the tank is installed spread on the roof, the waterproofing materials increase construction cost, as well as the environmental impact, though in HD3 this impact is inversely proportional to the amount of m^3 of collected rainwater.

Scenarios with the tank installed underground (LD1, LD4, HD1 and HD4) incur in pumping-related economic and environmental negative impacts during the stage of use, i.e. electricity consumption.

The highest savings in both, environmental and economic studies are achieved from the reduction in detergent and other additives used in laundry and that are reduced by the use of soft rainwater instead of Barcelona's hard tap water. Comparing the recommended dosage of detergent, for hard (1.59 doses per laundry) and soft water (1 dose per laundry), a difference of half the environmental impacts and of 0.57 euros per laundry, are gained. This way, when more users (more washing machines) are considered, more savings the system gets. Accordingly, the scenario with the higher amount of users (240 households or 240 washing machines) is the best scenario, mostly because the savings can faster cope with the high construction cost and obtain profits after that. This outcome is noticed in the rest of high density scenarios (HD1, HD2 and HD3) with 24 households each. This finding is significant because more cities around the world suffer from hard water problems due to limestone watersheds like Barcelona.

In LCA the reduced need for structural components to reinforce the building in order to absorb the weight of a full tank, was the decision point between the two scenarios with the tank installed on or distributed over the roof, resulting in a more environmentally friendly scenario with the tank distributed over the roof. In the case of Exergy analysis, the crucial element was the waterproofing foil, resulting in a more resource efficient scenario with the tank spread on the roof (Vargas-Parra et al. 2013). In LCC we could say "the more, the merrier" since the savings are calculated based on the number of users and this is the main source of savings and therefore profitability.

Related to climate change effect, LD scenarios can easily adapt to variation in precipitation without changing the infrastructure, and in the case of HD scenarios, the investment is recovered rapidly after a few years, in this way, a resizing of the system can be afforded.

There are other factors not considered in this study which could play a significant role, especially, in the economic feasibility of RWH system, such as potential technology improvement and/or other uses of rainwater. Technological advance will doubtless continue to reduce energy and water consumption in washing machines and other home appliances. For this study only laundry use was considered, other non-potable uses of rainwater could be toilet flushing and garden watering although, economic savings in these two cases would only include savings from tap water consumption. Studies on toilet flushing and garden irrigation using rainwater show that rainwater cistern accounts for 40-60% of the initial investment with unviable economic results with negative or low NPVs (Anand and Apul 2011; Roebuck et al. 2011).

Other potential savings that are not considered in this study are the savings related to the avoided CO_2 emissions. Tap water production process can incur on a life cycle carbon footprint of 0.1-0.7 kg of CO_2 equivalent/m^3 treated water in Barcelona Metropolitan Area (Marín et al. 2012). Considering the current carbon market pricing (13.5 euros per ton of CO_2 emissions (Kossoy and Guigon 2012)), the savings from avoided CO_2 emissions by using RWH system can range from 0.03 to 26 euros per year per scenario (depending on the scenario), and representing a 0.02% of the yearly savings. Another avoided environmental impact is the fact that with the RWH system, the transport and distribution of tap water is avoided and with this also 0.074 kg CO_2 emissions per m^3, according to Sanjuan-Delmás et al. (2014).

Conclusions

From this study, Rainwater Harvesting (RWH) systems are proved as a viable option when water is adequately used, from the environmental and economic points of view by the application of LCA and LCC analyses in urban areas for non-potable water uses, more specifically for domestic laundry purposes. High density scenarios present better environmental and economic outcomes, illustrating how higher demands allow higher economic profit and lower environmental impact per unit. Difference between hard tap water and soft rain water laundry additive requirements portend avoiding environmental impacts and economic cost by 80%.

This work has shown the environmental and economic performance of installing RWH system in a highly populated Mediterranean city. As with any effort in making urban metabolism more sustainable, it is important that local and regional factors are taken into consideration (e.g. inflation rate, city design, etc.) when applying to other regions. However, we hope to provide a protocol that can be used by other cities in assessing RWH system.

References

Abdulla FA, Al-Shareef AW (2009) Roof rainwater harvesting systems for household water supply in Jordan. Desalination 243:195–207

Aguadelluvia (2012) Aguadelluvia catalog 2012. http://www.aguadelluvia.es/?cookies_ok=1. Accessed 25 Nov 2012

Anand C, Apul DS (2011) Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets. J Environ Manage 92:419–428 . doi: 10.1016/J.JENVMAN.2010.08.005

Angrill S, Farreny R, Gasol CM, et al (2011) Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. Int J Life Cycle Assess 17:25–42 . doi: 10.1007/s11367-011-0330-6

Angrill S, Petit-Boix A, Morales-Pinzón T, et al (2017) Urban rainwater runoff quantity and quality – A potential endogenous resource in cities? J Environ Manage 189:14–21 . doi: 10.1016/j.jenvman.2016.12.027

Baeza Group (2012) BAEZA catalog 2012. http://mobile.baeza-sa.com/files/catalogos-pdf/Calorama_13.pdf. Accessed 21 Nov 2012

Banco de España (2013) Interest rate. http://www.bde.es/webbde/es/estadis/infoest/a1901.pdf. Accessed 14 Mar 2013

Barcelona City (2015) Superfície i densitat dels districtes i barris. 2015. http://www.bcn.cat/estadistica/catala/dades/anuari/cap01/C0101050.htm

Barrera-Escoda A, Cunillera J (2011) Primer informe sobre la generació d'escenaris climàtics regionalitzats per a Catalunya durant el segle XXI. Barcelona

Campisano A, Butler D, Ward S, et al (2017) Urban rainwater harvesting systems: Research, implementation and future perspectives. Water Res 115:195–209 . doi: 10.1016/j.watres.2017.02.056

Campisano A, Modica C (2012) Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily. Resour Conserv Recycl 63:9–16 . doi: 10.1016/j.resconrec.2012.03.007

Catalonia Meteorological Service (SMC) (2011) Daily time series of rainfall in Barcelona. http://www.meteo.cat/servmet/index.html. Accessed 20 Dec 2011

Cellura M, Ardente F, Longo S (2012) From the LCA of food products to the environmental assessment of protected crops districts: a case-study in the south of Italy. J Environ Manage 93:194–208 . doi: 10.1016/j.jenvman.2011.08.019

Colegio Oficial de Aparejadores (2012) COAATGU Guadalajara. Precio Centro de la Construcción. Gabinete Técnico. Aparejadores Guadalajara, SLU. http://www.preciocentro.com/

Debacker W, Allacker K, Spirinckx C, et al (2013) Identification of Environmental and Financial Cost Efficient Heating and Ventilation Services for a Typical Residential Building in Belgium. J Clean Prod null: . doi: 10.1016/j.jclepro.2013.05.037

Ebara (2012) Ebara Catalog 2012. http://www.ebara.es/documentacion_ebara.asp. Accessed 20 Nov 2012

European Commission (2007) Legislation. Off J Eur Communities 50:23 . doi: ISSN 1725-2555

European Environment Agency (2014) Environmental Terminology Discovery Service. http://glossary.eea.europa.eu/EEAGlossary/W/water_stress. Accessed 2 Jan 2014

Eurostat (2013) Concepts and Definitions Database. http://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL_GLOSSARY&StrNom=CODED2&StrLanguageCode=EN. Accessed 26 Feb 2013

Eurostat (2014) Eurostat regional yearbook 2013. Luxembourg

Farreny R, Gabarrell X, Rieradevall J (2011) Cost-efficiency of rainwater harvesting strategies in dense Mediterranean neighbourhoods. Resour Conserv Recycl 55:686–694 . doi: 10.1016/j.resconrec.2011.01.008

Food and Agriculture Organization of the United Nations (FAO) (2012) Water scarcity. www.fao.org/nr/water/topics_scarcity.html. Accessed 10 Mar 2012

Fragkou MC, Vicent T, Gabarrell X (2015) An ecosystemic approach for assessing the urban water self-sufficiency potential: lessons from the Mediterranean. Urban Water J 1–13 . doi: 10.1080/1573062X.2015.1024686

Frijia S, Guhathakurta S, Williams E (2011) Functional Unit, Technological Dynamics, and Scaling Properties for the Life Cycle Energy of Residences. Environ Sci Technol 46:7 . doi: 10.1021/es202202q

Gabarrell X, Morales-Pinzón T, Rieradevall J, et al (2014) Plugrisost: a model for design, economic cost and environmental analysis of rainwater harvesting in urban systems. Water Pract Technol 9:13 . doi: 10.2166/wpt.2014.028

Goedkoop M, Heijungs R, Huijbregts M, et al (2013) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Amersfoort, Netherlands

Graf Ibérica (2012) Graf Catalog 2012. http://www.grafiberica.com/descargas/catalogos.html. Accessed 25 Nov 2012

Haque MM, Rahman A, Samali B (2016) Evaluation of climate change impacts on rainwater harvesting. J Clean Prod 137:60–69 . doi: 10.1016/J.JCLEPRO.2016.07.038

Hasa (2012) Hasa catalog 2012. http://www.bombashasa.com/descargas. Accessed 20 Nov 2012

Imteaz MA, Ahsan A, Shanableh A (2013) Reliability analysis of rainwater tanks using daily water balance model: Variations within a large city. Resour Conserv Recycl 77: . doi: 10.1016/j.resconrec.2013.05.006

Imteaz MA, Shanableh A, Rahman A, Ahsan A (2011) Optimisation of rainwater tank design from large roofs: A case study in Melbourne, Australia. Resour Conserv Recycl 55:1022–1029 . doi: 10.1016/j.resconrec.2011.05.013

INSEE National Institute of Statistics and Economic Studies - France (2013) Insee - Population. http://www.insee.fr/fr/themes/theme.asp?theme=2

International Monetary Fund (IMF) (2012) World Economic Outlook Database. http://www.imf.org/external/pubs/ft/weo/2012/02/weodata/download.aspx. Accessed 25 Feb 2013

IPCC (2000) Special Report Emissions Scenarios (SRES). Cambridge University Press

ISO (2006) ISO 14040: environmental management - life cycle assessment - principles and framework. International Organization for Standardization. Geneva, Switzerland

ISO (2008) ISO 15686-5 - Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing. Nederlands Normalisatie-Institut. Delft, Netherlands

ITeC (2012) Institut de Tecnologia de la Construcció de Catalunya. MetaBase ITeC, Online ITeC database: prices, technical details, companies, certificates, product pictures and environmental data. http://www.itec.es/nouBedec.e/bedec.aspx. Accessed 28 Sep 2012

Kisakye V, Akurut M, Van der Bruggen B (2018) Effect of Climate Change on Reliability of Rainwater Harvesting Systems for Kabarole District, Uganda. Water 10:71 . doi: 10.3390/w10010071

Kossoy A, Guigon P (2012) State and Trends of the Carbon Market 2012

Leflaive X (2012) Water Outlook to 2050 : The OECD calls for early and strategic action. GWF Discussion Paper 1219. Canberra, Australia

Marín D, Juncà S, Massagué A, et al (2012) Impacts on climate change of three drinking water treatment plants supplying Barcelona Metropolitan Area. In: World Congress on Water, Climate and Energy. International Water Association, Dublin, pp 1–8

Maxwell S (2010) Historical water price trends. J Am Water Work Assoc 102:24–28

Met Office Hadley Centre for Climate Change (2009) Vision 2030. The resilience of water supply and sanitation in the face of climate change. Climate change projection study

Morales-Pinzón T, Rieradevall J, Gasol CM, Gabarrell X (2015) Modelling for economic cost and environmental analysis of rainwater harvesting systems. J Clean Prod 87:613–626 . doi: 10.1016/j.jclepro.2014.10.021

Peri G, Traverso M, Finkbeiner M, Rizzo G (2012) The cost of green roofs disposal in a life cycle perspective: Covering the gap. Energy 48:406–414 . doi: 10.1016/j.energy.2012.02.045

Rahman A, Keane J, Imteaz MA (2012) Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits. Resour Conserv Recycl 61:16–21 . doi: 10.1016/j.resconrec.2011.12.002

Rahman S, Khan MTR, Akib S, et al (2014) Sustainability of rainwater harvesting system in terms of water quality. ScientificWorldJournal 2014:721357 . doi: 10.1155/2014/721357

Remosa (2012) Remosa Catalog 2012. http://www.remosa.net/productos/. Accessed 29 Jul 2014

Roebuck RM, Oltean-Dumbrava C, Tait S (2011) Whole life cost performance of domestic rainwater harvesting systems in the United Kingdom. Water Environ J 25:355–365 . doi: 10.1111/j.1747-6593.2010.00230.x

RTVE Radio y Televisión Española (2014) RTVE enquiry “water price in Spain”

Saci (2012) Saci catalog 2012. http://www.sacipumps.com/docs.cfm/esp/catalogos.htm. Accessed 21 Nov 2012

Sandin G, Peters GM, Svanström M (2014) Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int J Life Cycle Assess 19:723–731 . doi: 10.1007/s11367-013-0686-x

Sanjuan-Delmás D, Petit-Boix A, Gasol CM, et al (2014) Environmental assessment of drinking water transport and distribution network use phase for small to medium-sized municipalities in Spain. J Clean Prod Press

Saouter E, Hoof G van (2002) A database for the life-cycle assessment of procter & gamble laundry detergents. Int J Life Cycle Assess 7:103–114 . doi: 10.1007/BF02978854

Solomon S, Qin D, Manning M, et al (2007) Climate Change 2007: The Physical Science Basis. Contribution of working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA

The World Bank (2009) Water and Climate Change : Understanding the Risks and Making Climate-Smart Investment Decisions

United Nations Development Programme (2006) Human Development Report 2006 Beyond scarcity: Power, poverty and the global water crisis. New York, USA

United Nations Environment Programme (UNEP) (2007) Fourth Global Environment Outlook: Environment for Development. http://www.unep.org/geo/GEO4/report/GEO-4_Report_Full_en.pdf. Accessed 21 Jan 2012

Vargas-Parra MV, Villalba G, Gabarrell X (2013) Applying exergy analysis to rainwater harvesting systems to assess resource efficiency. Resour Conserv Recycl 72:50–59 . doi: 10.1016/j.resconrec.2012.12.008

Wastewater Gardens International (2010) International water consumption. http://www.wastewatergardens.com/pdf/WWG_InfoSheet_InternationalWaterConsump.pdf. Accessed 30 Jul 2014

Wong NH, Tay SF, Wong R, et al (2003) Life cycle cost analysis of rooftop gardens in Singapore. Build Environ 38:499–509 . doi: 10.1016/S0360-1323(02)00131-2

World Water Assessment Programme (WWAP) (2006) The State of the Resource, World Water Development Report 2, Chapter 4. //www.unesco.org/water/wwap/wwdr2/pdf/wwdr2_ch_4.pdf

World Water Assessment Programme (WWAP) (2012) The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk. París

World Water Assessment Programme (WWAP) (2009) The United Nations World Water Development Report 3: Water in a Changing World. http://unesdoc.unesco.org/images/0018/001819/181993e.pdf. Accessed 8 Jan 2013

WQA (2010) Softened Water benefits Study: Energy Savings and Detergent Savings

Tables and figures

Table 1 Scenarios description

Scenario	Construction type	Scale		Tank size (m^3)	Tank layout	Catchment area (m^2)	Rainwater supply (m^3/year)	Laundry demand (m^3/year)	Rainwater supply / Laundry demand
LD1				5	Underground	250	24.5	25	98%
LD2	Individual	1 Household		5	Below roof	250	24.5	25	98%
LD3				9	Spread on roof	250	24.5	25	98%
LD4	Cluster	4 Household		20	Underground	1000	99	100	99%
HD1				20	Underground	700	283	600	47%
HD2	Individual	1 Building	24 households	20	Below roof	700	283	600	47%
HD3				21	Spread on roof	700	283	600	47%
HD4	Cluster	10 Buildings	240 households	209	Underground	7000	2824	6000	47%

NOTE: LD(X): Low Density scenario HD(X): High Density scenario

Table 2 Inventory of materials and energy per functional unit.

Stage	Short name	measuring unit	LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Construction	Particle board	m^3	1.05E-03	7.66E-04	0.00E+00	6.36E-04	2.29E-04	1.64E-04	0.00E+00	1.07E-04
	Concrete	m^3	3.47E-03	4.81E-03	3.36E-03	3.05E-03	1.11E-03	1.11E-03	1.28E-03	1.03E-03
	Steel	kg	3.22E-01	6.54E-01	1.03E-01	2.38E-01	2.33E-01	2.33E-01	2.29E-02	9.24E-02
	Glass Fibre + Polyvinyldenchloride	kg	0.00E+00	0.00E+00	4.25E-02	0.00E+00	0.00E+00	0.00E+00	1.52E-02	0.00E+00
		kg	0.00E+00	0.00E+00	4.25E-02	0.00E+00	0.00E+00	0.00E+00	1.52E-02	0.00E+00
	Brick	kg	0.00E+00	0.00E+00	3.37E-01	0.00E+00	0.00E+00	0.00E+00	6.83E-02	0.00E+00
	Light mortar	kg	0.00E+00	0.00E+00	4.05E-02	0.00E+00	0.00E+00	0.00E+00	8.20E-03	0.00E+00
	Polypropylene	kg	3.04E-03	2.35E-03	2.35E-03	2.03E-02	7.08E-03	4.10E-03	4.10E-03	1.31E-02
	Chromium Steel	kg	1.93E-02	0.00E+00	0.00E+00	9.54E-03	7.35E-03	0.00E+00	0.00E+00	1.47E-03
	Diesel	kg	2.69E-02	0.00E+00	0.00E+00	1.11E+00	4.01E-01	0.00E+00	0.00E+00	6.15E-01
	Transport lorry 7.5-16 tons	tkm	2.60E-01	3.67E-01	2.59E-01	2.28E-01	8.74E-02	8.73E-02	9.63E-02	7.77E-02
Use	Electricity	kWh	4.90E-01	0.00E+00	0.00E+00	9.70E-01	4.90E-01	0.00E+00	0.00E+00	8.40E-01
EOL	Diesel	kg	1.97E-02	4.79E-01	2.39E-01	6.68E-01	2.34E-01	1.53E-01	8.67E-02	5.91E-01
	Transport lorry 7.5-16 tons	tkm	4.56E-01	6.42E-01	4.54E-01	3.99E-01	1.53E-01	1.53E-01	1.69E-01	1.36E-01

Table 3. Total cost in euros

CONSTRUCTION STAGE		LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Storage tank	Different capacities of prefabricated tanks for scenarios LD1, LD2, LD4, HD1, HD2, HD4. For scenarios LD3 and HD3 all necessary materials to construct and install the tank distributed over the roof.	2,083.0	2,083.0	2,288.4	5,670.0	5,670.0	5,670.0	9,355.1	60,155.0
Emplacement materials	Sand from recycled materials, waterproofing sheet, steel frame to reinforce structure.	28.9	0.0	3,355.9	57.9	57.9	0.0	13,172.3	115.9
Polypropylene pipes	Polypropylene copolymer PP-R 25 mm y 4.2 mm S 2.5	65.9	50.9	50.9	1,773.8	306.6	156.2	156.2	4,986.9
Pump	Multi-stage, integral, centrifugal, horizontal electric pumps	500.0	0.0	0.0	500.0	500.0	0.0	0.0	500.0
Filters	Universal external filter strainer with DN 100 inlet ring	390.0	390.0	390.0	390.0	390.0	390.0	390.0	390.0
Construction services	Manpower for excavation, installation and dirt transportation	310.5	186.4	40.5	623.3	640.1	328.8	44.5	4,315.8
Pump replacement (every 10 years)	Multi-stage, integral, centrifugal, horizontal electric pumps	500.0	0.0	0.0	500.0	500.0	0.0	0.0	500.0
Filter replacement (every 5 years)	Universal external filter strainer with DN 100 inlet ring	390.0	390.0	390.0	390.0	390.0	390.0	390.0	390.0
Maintenance services (every 5 years)	Cleaning tank and filter, and replacement of pump and filter when necessary	134.4	38.4	38.4	153.6	152.4	57.1	57.1	171.4
Transport of materials	Transport of the materials from industry to site of construction <30 km.	59.8	0.0	0.0	239.4	251.4	0.0	0.0	2,501.7

USE STAGE		LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Electricity (yearly)	Electricity consumption for pumping water. Prices from http://www.energy.eu/ consulted in 2013	2.5	0.0	0.0	19.8	122.3	0.0	0.0	244.5
END OF LIFE STAGE		LD1	LD2	LD3	LD4	HD1	HD2	HD3	HD4
Deconstruction services	Manpower for excavation and dismantling	857.7	869.7	1,514.9	3,374.1	3,538.4	3,538.4	6,311.1	34,902.7

Table 4 Avoided environmental impacts from savings in detergent per functional unit.

Impact	per m^3	LD1	HD3
Climate change (kg CO_2 eq)	1.45E+00	3.54E+01	4.09E+02
Ozone depletion (kg CFC-11 eq)	3.54E-05	8.68E-04	1.00E-02
Terrestrial acidification (kg SO_2 eq)	1.33E-02	3.25E-01	3.76E+00
Freshwater eutrophication (kg P eq)	1.71E-01	4.19E+00	4.85E+01
Photochemical oxidant formation (kg NMVOC)	5.35E-03	1.31E-01	1.51E+00
Particulate matter formation (kg PM10 eq)	1.07E-07	2.63E-06	3.04E-05
Cumulative Energy Demand (MJ)	2.56E+01	6.27E+02	7.25E+03
Cumulative Exergy Demand (MJ)	2.86E+01	6.99E+02	8.09E+03

Table 5. NPV, IRR, and PB for low and high density.

		Financial analysis		
		NPV (Euros)	IRR* (%)	PB* (years)
Low density scenarios				
Individual construction	LD1	- 1,800.1		-
	LD2	1,045.9	2.5%	21.2
	LD3	- 2,794.4		-
Cluster construction	LD4	12,603.9	6.0%	14.4
High density scenarios				
Individual construction	HD1	66,192.6	31.3%	2.9
	HD2	74,694.1	45.8%	2.1
	HD3	56,302.0	9.2%	10.4
Cluster construction	HD4	753,896.5	37.8%	2.6

* When the investment project does not overcome the initial expenses, the project has a negative NPV and IRR and PB cannot be calculated.

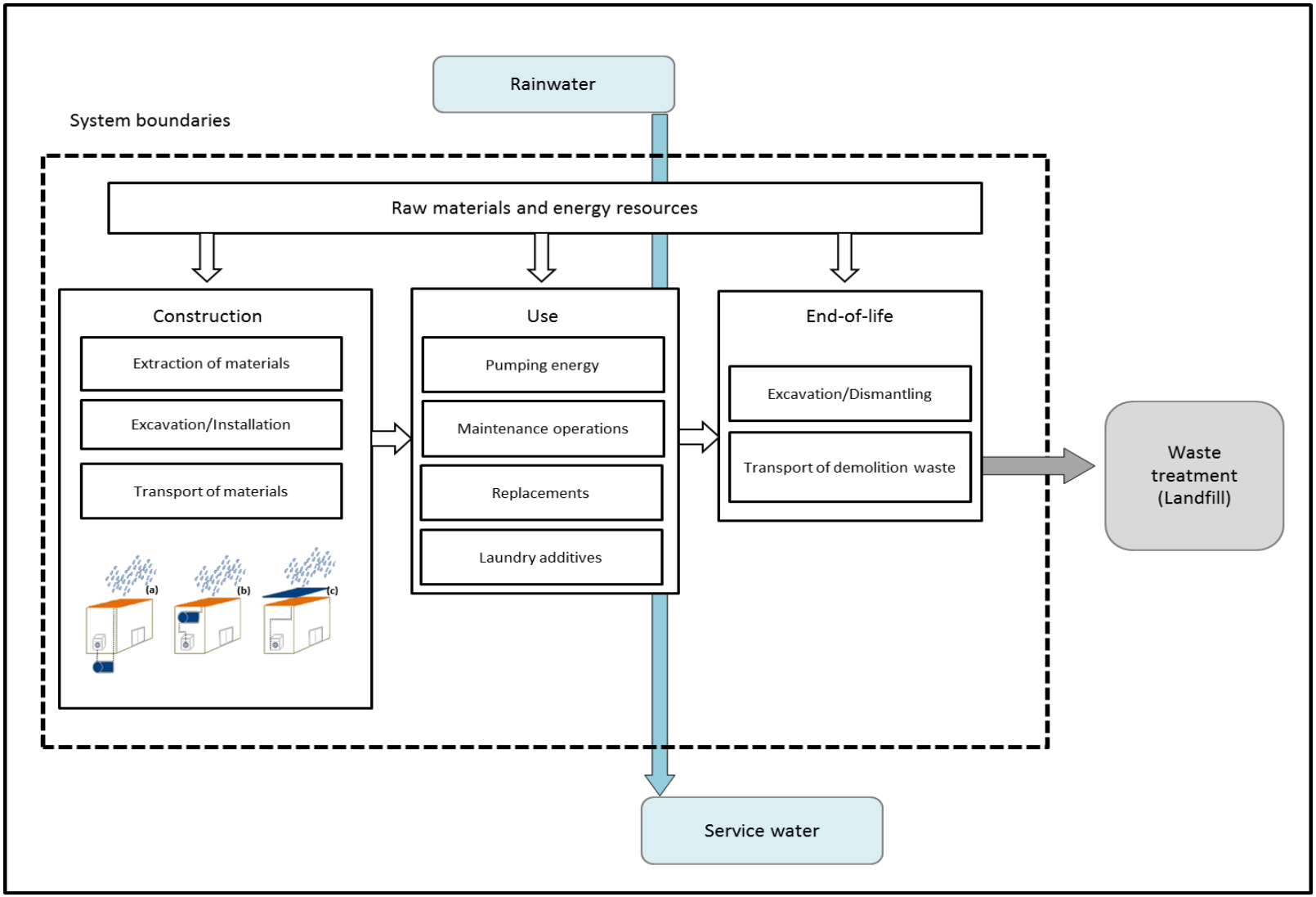

Figure 1 RWH system boundaries and basic components with three different storage positions a) underground, b) below the roof and c) spread on the roof.

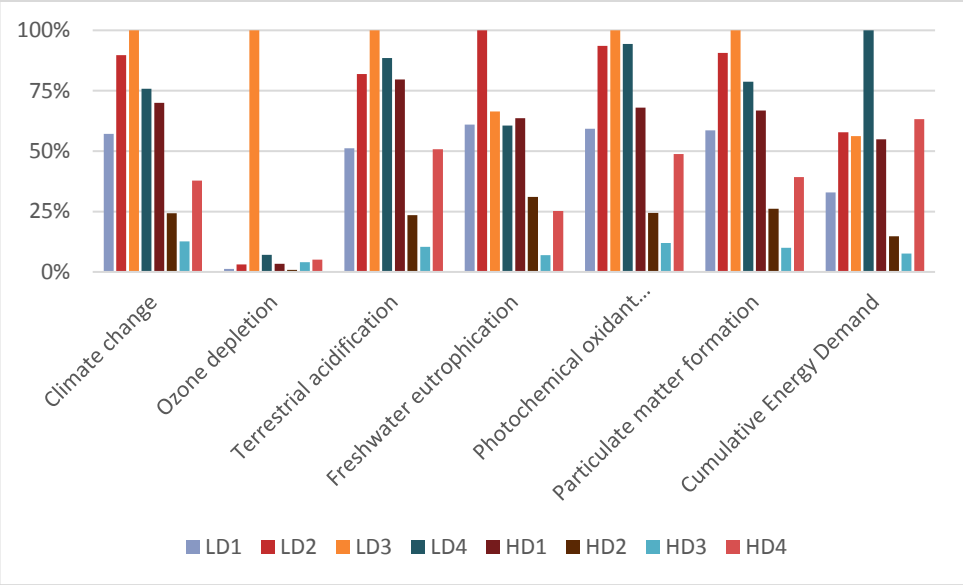

Figure 2 Comparison of all eight scenarios for selected impact categories per cubic meter.

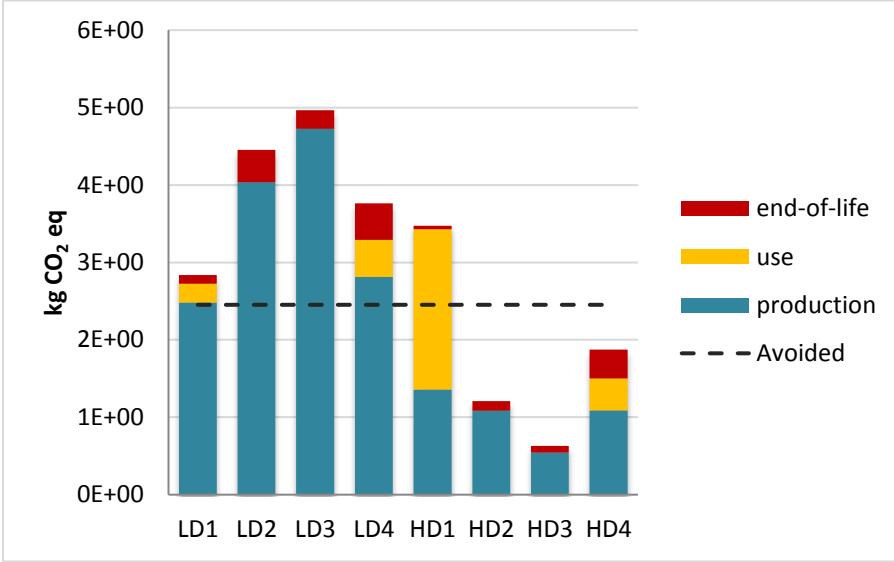

Figure 3 Results in climate change impact category and life cycle stage contribution for each scenario per cubic meter

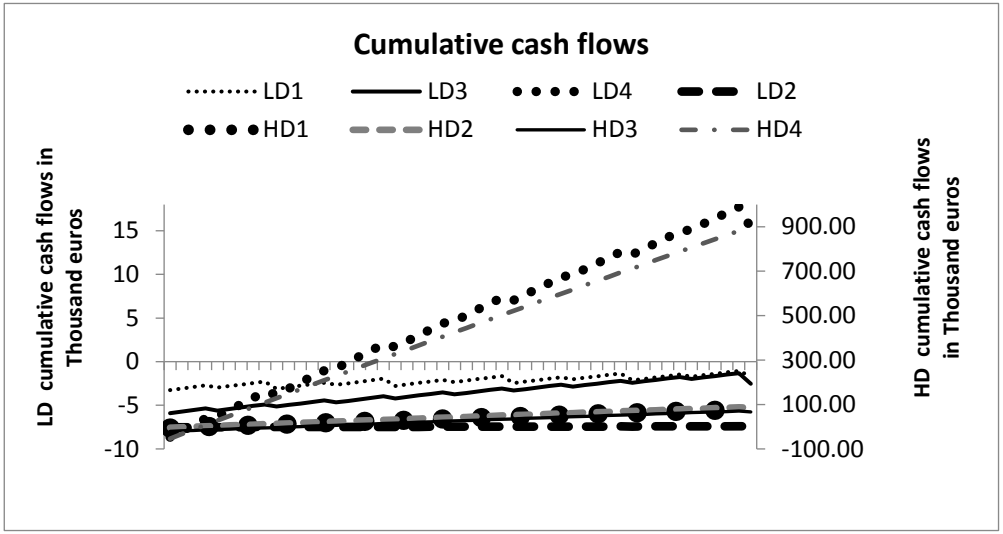

Figure 4 Cumulative cash flows (50 years) for LD and HD scenarios.

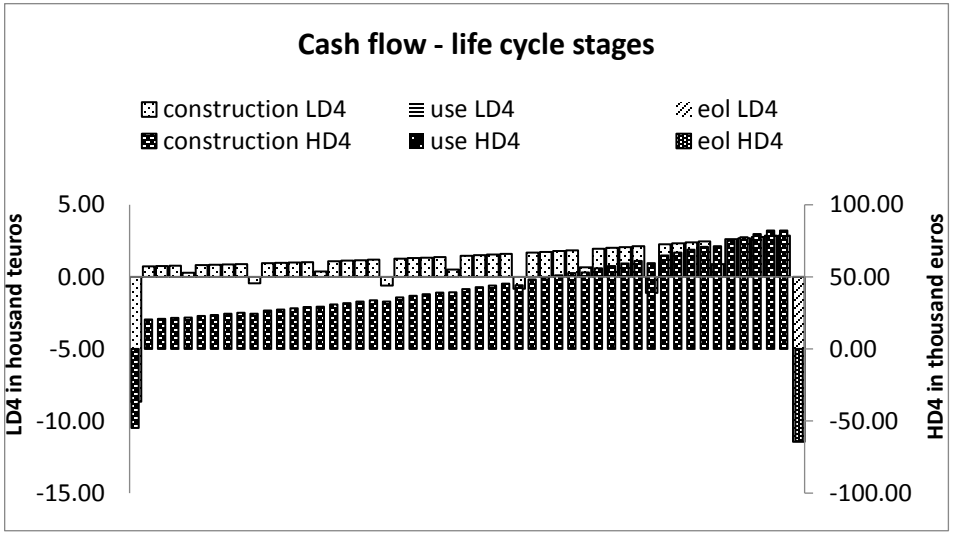

Figure 5 Cash flows by life cycle stage of scenarios LD4 and HD4.

Supporting information

Table S1. Cost inventory

Stage	Input	units	Material cost	Labor cost	Total	LOW DENSITY								HIGH DENSITY							
						LD1		LD2		LD3		LD4		HD1		HD2		HD3		HD4	
						QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST	QUANTITY	COST
Construction stage	5.800 litres, prefabricated concrete tank	unit	2083.00		2083.00	1.00	2,083.00	1.00	2,083.00	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	21.000 litres, (3) prefabricated concrete tank	unit	5670.00		5670.00	0.00	-	0.00	-	0.00	-	1.00	5,670.00	1.00	5,670.00	0.00	-	0.00	-	0.00	-
	40.000 litres, (5) prefabricated concrete tank.	unit	11298.00			0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	11,298.00	0.00	-	4.00	45,192.00
	11.600 litres, (2) prefabricated concrete tank.	unit	3665.00			0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	3,665.00
	Pavement & installation	m2	14.09	7.42	21.51	0.00	-	0.00	-	100.00	2,150.56	0.00	-	0.00	-	0.00	-	420.00	9,032.34	0.00	-
	Sand backfilling	m3	27.72	1.26	28.98	1.00	28.98	0.00	-	0.00	-	2.00	57.95	2.00	57.95	0.00	-	0.00	-	4.00	115.90
	Reinforced concrete for pillars	kg	0.85	0.25	1.10	0.00	-	0.00	-	126.00	138.62	0.00	-	0.00	-	0.00	-	324.32	356.81	0.00	-
	Reinforced concrete for walls	kg	0.85	0.40	1.25	0.00	-	0.00	-	126.00	157.63	0.00	-	0.00	-	0.00	-	324.32	405.72	0.00	-
	Reinforced concrete for slabs	kg	0.85	0.29	1.13	0.00	-	0.00	-	126.00	142.86	0.00	-	0.00	-	0.00	-	324.32	367.72	0.00	-

Waterproofing sheetPVC-P with fibreglass.	m2	19.82	8.22	28.05	0.00	-	0.00	-	104.00	2,916.84	0.00	-	0.00	-	0.00	-	429.36	12,042.07	0.00	-
Double air brick (10 cm)	m2	4.95	13.90	18.85	0.00	-	0.00	-	4.00	75.41	0.00	-	0.00	-	0.00	-	9.36	176.47	0.00	-
Amorphous isolation (2 cm), with mortar and concrete.	m2	1.89	13.74	15.63	0.00	-	0.00	-	4.00	62.51	0.00	-	0.00	-	0.00	-	9.36	146.28	0.00	-
Polypropylene copolymer pipeline	m	15.79	7.35	23.14	2.85	65.95	2.20	50.91	2.20	50.91	76.65	1,773.78	13.25	306.62	6.75	156.20	6.75	156.20	215.50	4,986.94
Multistage centrifugal electric pump	unit	500.00	0.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00
Basket type filter pit surface max. collection: 350m2	unit	390.00		390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00
Excavation of trenches and pits.	h	0.00	7.70	7.70	5.00	38.50	5.00	38.50	9.00	69.30	20.00	154.00	21.00	161.70	21.00	161.70	37.80	291.06	209.00	1,609.30
7 tons truck for soil transportation to a waste management plant	h	0.00	7.75	7.75	5.00	38.75	5.00	38.75	9.00	69.75	20.00	155.00	21.00	162.75	21.00	162.75	37.80	292.95	209.00	1,619.75
Earthmoving with shovel	h	0.00	15.77	15.77	5.00	78.85	5.00	78.85	9.00	141.93	20.00	315.40	21.00	331.17	21.00	331.17	37.80	596.11	209.00	3,295.93
24 tons truck for soil transportation to a waste management plant	h	0.00	4.22	4.22	5.00	21.10	5.00	21.10	9.00	37.98	20.00	84.40	21.00	88.62	21.00	88.62	37.80	159.52	209.00	881.98

	12 tons, self-propelled crane	h	0.00	48.98	48.98	2.00	97.96	3.00	146.94	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	20 tons, self-propelled crane	h	0.00	57.07	57.07	0.00	-	0.00	-	0.00	-	3.00	171.21	3.00	171.21	5.00	285.35	0.00	-	0.00	-
	60 tons, self-propelled crane	h	0.00	109.89	109.89	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	8.00	879.12
	Journeyman Plumber	h	0.00	19.05	19.05	5.00	95.25	0.00	-	0.00	-	5.00	95.25	5.00	95.25	0.00	-	0.00			
	Journeyman Plumber (every 5 years)	h	0.00	19.05	19.05	2.00	38.41	2.00	38.41	2.00	38.41	3.00	57.62	3.00	57.15	3.00	57.15	3.00	-	5.00	95.25
	Journeyman Plumber (every 10 years)	h	0.00	19.05	19.05	5.00	96.03	0.00	-	0.00	-	5.00	96.03	5.00	95.25	0.00	-	0.00			
	Multistage centrifugal electric pump (every 10 years)	unit	500.00	0.00	500.00	1.00	500.00	0.00	-	0.00	-	1.00	500.00	1.00	500.00	0.00	-	0.00			
	Basket type filter pit surface max. collection: 350m2. (every 5 years)	unit	390.00		390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00	390.00	1.00			
Use stage	Electricity (yearly)	kWh			0.21	600.00	123.69	0.00	-	0.00	-	4800.00	989.52	59304.96	6,112.86	0.00	-	0.00	-	118609.92	12,225.72
End-of-life stage	12 tons transport truck	h	0.00	38.50	38.50	1.00	36.30	0.00	-	1.00	36.30	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-
	20 tons transport truck	h	0.00	48.25	48.25	0.00	-	1.00	48.30	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-

45 tons semi trailer truck	h	0.00	88.32	88.32	0.00	-	0.00	-	0.00	-	1.00	88.32	1.00	88.32	1.00	88.32	0.00	-	0.00	-
60 tons semi trailer truck	h	0.00	100.95	100.95	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	1.00	100.95	0.00	-
25 tons semi trailer truck with platform	h	0.00	37.74	37.74	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	0.00	-	15.00	566.10
Full demolition, no sorting of waste and load on truck	m3	0.00	10.57	10.57	5.00	52.85	5.00	52.85	9.00	95.13	20.00	211.40	21.00	221.97	21.00	221.97	37.80	399.55	209.00	2,209.13
Demolition of retaining wall, load on truck	m3	0.00	147.81	147.81	5.00	739.05	5.00	739.05	9.00	1,330.29	20.00	2,956.20	21.00	3,104.01	21.00	3,104.01	37.80	5,587.22	209.00	30,892.29
Demolition of slope formation, load on truck	m3	0.00	5.91	5.91	5.00	29.55	5.00	29.55	9.00	53.19	20.00	118.20	21.00	124.11	21.00	124.11	37.80	223.40	209.00	1,235.19

Table S2 Characterization results per functional unit.

		CC	OD	TA	FE	POF	PMF	CED
LD1	TOTAL	2.84E+00	2.54E-07	1.15E-02	8.42E-04	1.00E-02	5.75E-03	4.99E+01
	PRODUCTION	2.48E+00	1.86E-07	9.82E-03	7.84E-04	8.83E-03	5.17E-03	4.19E+01
	USE	2.42E-01	3.66E-08	1.30E-03	4.93E-05	7.27E-04	4.01E-04	5.18E+00
	END-OF-LIFE	1.12E-01	3.17E-08	4.21E-04	9.03E-06	4.58E-04	1.76E-04	2.76E+00
LD2	TOTAL	4.45E+00	6.30E-07	1.85E-02	1.38E-03	1.58E-02	8.91E-03	8.76E+01
	PRODUCTION	4.04E+00	2.74E-07	1.56E-02	1.34E-03	1.35E-02	8.00E-03	5.77E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	4.17E-01	3.56E-07	2.86E-03	3.97E-05	2.28E-03	9.07E-04	2.99E+01
LD3	TOTAL	4.96E+00	2.06E-05	2.25E-02	9.17E-04	1.69E-02	9.82E-03	8.52E+01
	PRODUCTION	4.73E+00	2.04E-05	2.10E-02	8.95E-04	1.56E-02	9.33E-03	6.98E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	2.38E-01	1.83E-07	1.52E-03	2.21E-05	1.25E-03	4.96E-04	1.54E+01
LD4	TOTAL	3.76E+00	1.46E-06	2.00E-02	8.37E-04	1.59E-02	7.73E-03	1.51E+02
	PRODUCTION	2.81E+00	9.09E-07	1.38E-02	6.92E-04	1.17E-02	5.83E-03	1.01E+02
	USE	4.79E-01	7.24E-08	2.57E-03	9.75E-05	1.44E-03	7.94E-04	1.02E+01
	END-OF-LIFE	4.73E-01	4.78E-07	3.65E-03	4.69E-05	2.76E-03	1.11E-03	4.00E+01
HD1	TOTAL	3.47E+00	6.89E-07	1.80E-02	8.78E-04	1.15E-02	6.57E-03	8.30E+01
	PRODUCTION	1.36E+00	3.54E-07	6.64E-03	4.53E-04	5.05E-03	3.06E-03	3.69E+01
	USE	2.07E+00	3.13E-07	1.11E-02	4.21E-04	6.21E-03	3.43E-03	4.43E+01
	END-OF-LIFE	4.69E-02	2.19E-08	2.23E-04	4.01E-06	2.13E-04	8.29E-05	1.87E+00
HD2	TOTAL	1.21E+00	1.87E-07	5.30E-03	4.29E-04	4.13E-03	2.57E-03	2.24E+01
	PRODUCTION	1.09E+00	7.51E-08	4.42E-03	4.17E-04	3.45E-03	2.29E-03	1.31E+01
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	1.22E-01	1.12E-07	8.78E-04	1.18E-05	6.85E-04	2.73E-04	9.38E+00
HD3	TOTAL	6.29E-01	8.18E-07	2.35E-03	9.63E-05	2.03E-03	9.87E-04	1.15E+01
	PRODUCTION	5.41E-01	7.52E-07	1.79E-03	8.82E-05	1.57E-03	8.06E-04	5.88E+00
	USE	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	END-OF-LIFE	8.73E-02	6.68E-08	5.57E-04	8.12E-06	4.59E-04	1.82E-04	5.62E+00
HD4	TOTAL	1.87E+00	1.05E-06	1.15E-02	3.48E-04	8.25E-03	3.86E-03	9.57E+01
	PRODUCTION	1.09E+00	5.77E-07	6.16E-03	2.26E-04	4.74E-03	2.26E-03	5.22E+01
	USE	4.15E-01	6.27E-08	2.22E-03	8.45E-05	1.25E-03	6.88E-04	8.87E+00
	END-OF-LIFE	3.71E-01	4.14E-07	3.07E-03	3.78E-05	2.26E-03	9.08E-04	3.46E+01

Table S3. Detergent inventory per cubic meter.

gr	Input
147.9	Water
2.1	Fluorescent whitening agent, DAS1
177.1	Sodium percarbonate
119.8	Sodium perborate, tetrahydrate
90.6	Sodium perborate, monohydrate
209.4	Zeolite
31.3	Layered sodium silicate, SKS-6
20.8	Ethoxylated alcohol (AE11)
41.7	Ethoxylated alcohol (AE7)
81.3	Alkylbenzene sulfonate
5.2	Fatty alcohol sulfate
4.2	Sodium sulfate, anhydrite
41.7	EDTA, ethylenediaminetetraacetic acid

Table S4. Inflation sensitivity analysis results by financial tool.

INFLATION SENSITIVITY ANALYSIS			
SCENARIO	BASE (-0.2%)	ALTERNATIVE 1 (IMF forecast)	ALTERNATIVE 2 (none)
NPV (euros)			
LD1	-1,800.07	-1,351.58	-1,754.73
LD2	1,045.99	2,536.57	1,189.84
LD3	-2,794.42	-1,875.96	-2,696.39
LD4	12,603.88	22,183.09	13,515.88
HD1	66,192.65	102,582.16	69,573.09
HD2	74,694.14	114,706.53	78,410.42
HD3	56,302.02	93,856.01	59,821.36
HD4	753,896.55	1,162,355.92	791,841.86
IRR (%)			
LD1			
LD2	2.48%	4.23%	3.00%
LD3			
LD4	6.05%	7.84%	5.89%
HD1	31.34%	33.15%	31.60%
HD2	45.83%	47.59%	46.12%
HD3	9.20%	11.02%	9.42%
HD4	37.78%	39.59%	38.05%
PB (years)			
LD1	50.00	50.00	50.00
LD2	21.23	21.19	25.65
LD3	50.00	50.00	50.00
LD4	14.40	13.08	14.24
HD1	2.99	3.00	3.03
HD2	2.12	2.10	2.11
HD3	10.37	9.77	10.48
HD4	2.62	2.59	2.61

Table S5. Precipitation sensitivity analysis results by financial tool.

PRECIPITATION SENSITIVITY ANALYSIS				
SCENARIO	BASE ALTERNATIVE	ALTERNATIVE 1 (-1%)	ALTERNATIVE 2 (IPCC A2)	ALTERNATIVE 3 (IPCC B1)
		NPV (euros)		
LD1	-1,800.07	-3,286.69	-2,241.79	-1,885.49
LD2	1,045.99	-440.63	604.27	960.57
LD3	-2,794.42	-4,281.04	-3,236.14	-2,879.84
LD4	12,603.88	12,306.94	12,524.69	12,585.85
HD1	66,192.65	49,003.17	61,085.11	65,204.96
HD2	74,694.14	57,504.67	69,586.61	73,706.45
HD3	56,302.02	39,112.55	51,194.49	55,314.33
HD4	753,896.55	745,426.44	751,637.85	753,382.41
		IRR (%)		
LD1				
LD2	2.48%		1.82%	2.36%
LD3				
LD4	6.05%	5.95%	6.02%	6.04%
HD1	31.34%	29.84%	30.94%	31.27%
HD2	45.83%	44.31%	45.43%	45.76%
HD3	9.20%	8.03%	8.89%	9.14%
HD4	37.78%	37.39%	37.67%	37.76%
		PB (years)		
LD1	50.00	50.00	50.00	50.00
LD2	21.23	50.00	24.42	23.76
LD3	50.00	50.00	50.00	50.00
LD4	14.40	14.54	14.43	14.40
HD1	2.99	3.11	3.06	3.05
HD2	2.12	2.15	2.13	2.12
HD3	10.37	11.25	10.76	10.62
HD4	2.62	2.65	2.63	2.62

Table S6. Water price sensitivity analysis results by financial tool.

WATER PRICE SENSITIVITY ANALYSIS		
SCENARIO	BASE	ALTERNATIVE (6% increment)
	NPV (euros)	
LD1	-1,800.07	5,736.15
LD2	1,045.99	8,582.21
LD3	-2,794.42	4,741.80
LD4	12,603.88	43,087.49
HD1	66,192.65	153,332.68
HD2	74,694.14	161,834.18
HD3	56,302.02	143,442.06
HD4	753,896.55	1,623,449.39
	IRR	
LD1		4.03%
LD2	2.48%	6.64%
LD3		2.65%
LD4	6.05%	9.05%
HD1	31.34%	33.71%
HD2	45.83%	48.15%
HD3	9.20%	11.59%
HD4	37.78%	39.97%
	PB	
LD1	50	30.39
LD2	21.23	19.46
LD3	50	32.62
LD4	14.40	12.82
HD1	2.99	2.90
HD2	2.12	2.07
HD3	10.37	9.72
HD4	2.62	2.55

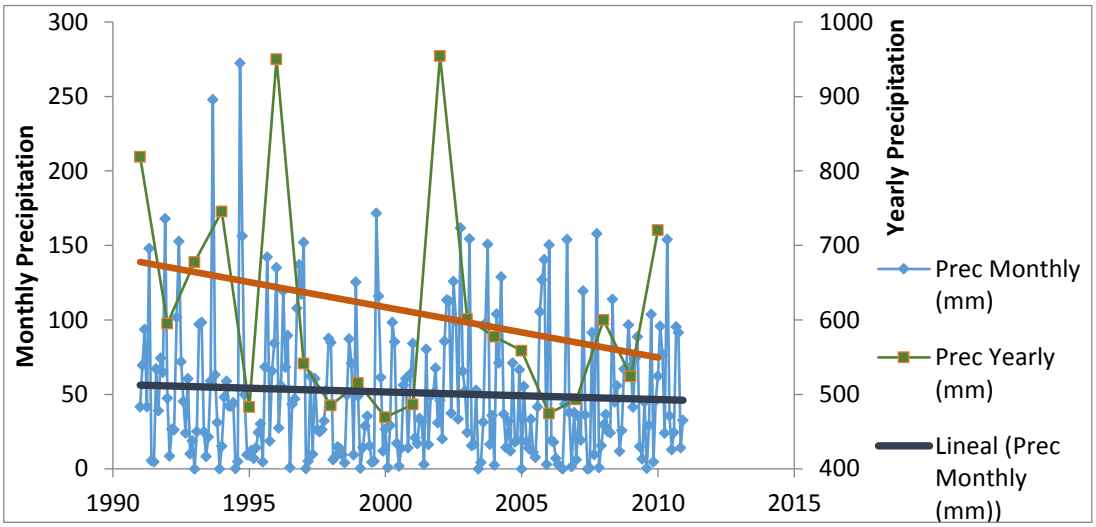

Figure S1. Monthly and yearly precipitation (1991-2010).

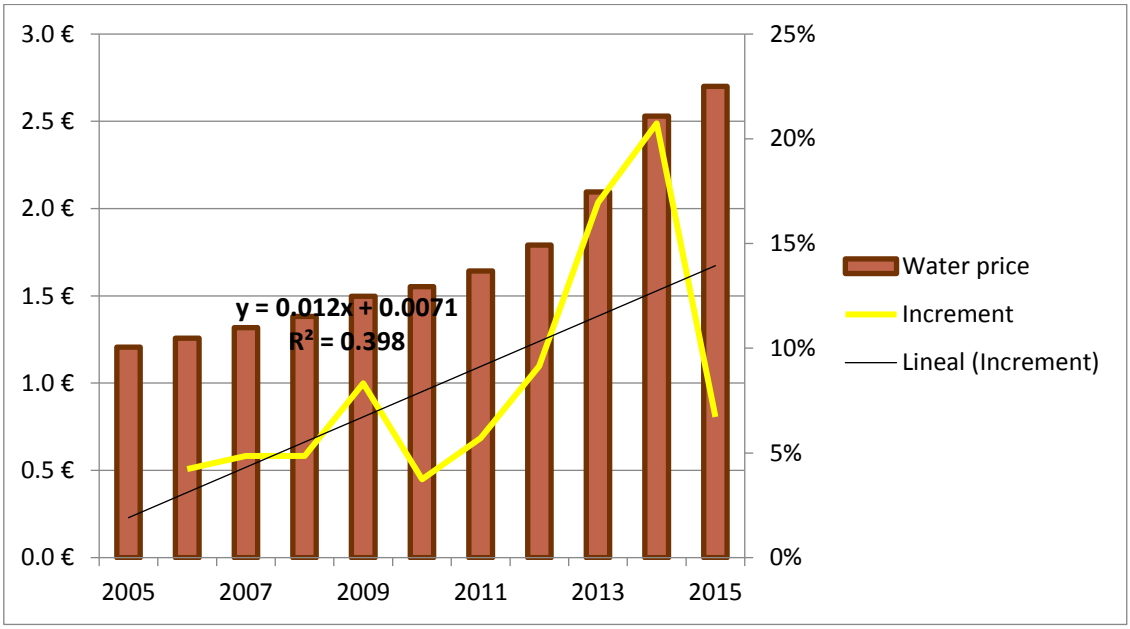

Figure S2. Tap water price evolution in Barcelona (2005-2015) Data from: Agència Catalana de l'Aigua 2009, 2010, 2011, 2012, 2013, 2014.

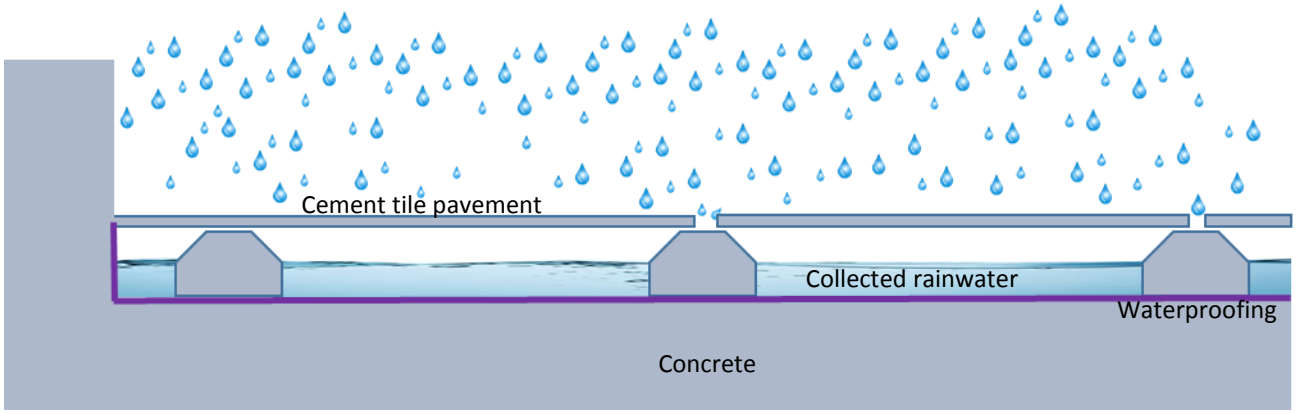

Figure S3. Rainwater tank distributed over the roof (Profile)