Technical-economic evaluation of rainwater harvesting systems in commercial buildings – Case studies from Sonae Sierra

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Abstract:

Water is an essential and increasingly scarce resource that should be preserved. The evolution of human population and communities has contributed to the global decrease of potable water availability and therefore, the reduction of its consumption is compulsory. Rainwater harvesting systems are emerging as a viable alternative source for water consumption in non-potable uses, such as toilet flushes, cooling towers, irrigation, fountains, cleaning services, among others.

This research aims to contribute to the promotion of water efficiency, focusing on the application of rainwater harvesting systems (RWHS) to commercial buildings. A technical evaluation tool was developed and complemented by a comparative financial analysis of the different alternatives in order to select the most adequate investment. The validation of the technical tool was performed through the comparison of the observed water savings from the RWHS in operation at the Colombo Shopping Centre, in Lisbon (9,4%), with the savings estimated by the tool (9,4%). The technical tool and the financial analysis were applied to two of Sonae Sierra's shopping centers to define the most viable RWHS configuration in each case. The installation of a 200m^3 is advised for the first case-study, located in Viana do Castelo, Portugal, allowing non-potable water savings of 60% and a payback period of about 25 years. In the case-study located in São Paulo, Brazil, the implementation of a 100 to 400m^3 tank is advised, leading to estimated non-potable savings between 20 and 50% and a payback period under two years.

Keywords: Rainwater harvesting systems; Commercial buildings; Technical-economic feasibility; Technical evaluation tool.

1. Introduction

Water is actively involved in life's development and species evolution, but Humans have an increasingly higher impact on the water cycle, both on quantity and quality of the water resources.

Seawater, for example, is highly susceptible to contaminations such as oil spills, garbage presence, incorrect processing of industry's chemical products, among others. Regarding the available fresh water, groundwater is even more abundant than surface water, and therefore should be preserved (Machado 2014).

Contamination of such resources, when combined with increasingly high consumption of potable water and therapid growth of the world population, will sooner or later lead to serious water shortages. In Australia, for example, it is estimated that these factors contribute to a 33-58% increase of domestic water consumption by 2031 (Birrell & Smith 2005).

2. Literature review

2.1. Global water consumption

In countries such as Australia, China, South Korea, Syria, Holland, Germany, the UK and Portugal, it is estimated that water consumption in residential buildings can vary from 120 to 200 liters/habitant.day, (Willis et al. 2008; Lu & Smout 2008; Schuetze & Santiago-Fandiño 2013; Mourad et al. 2011; Parker & Wilby 2012; Cristina Matos et al. 2013), leading to an average value of 150 liters/habitant.day.

However, not all residential water uses require potable water, such as toilet flushes and laundry machines, that represent about 50% of the domestic water consumption (Willis et al. 2008; Parker & Wilby 2012; Mourad et al. 2011; Schuetze & Santiago-Fandiño 2013). In commercial buildings, that percentage may even achieve 75% (Proença & Ghisi 2010).

There is also an increased global concern for environmental protection, leading to the study and development of several alternative measures. Regarding water consumption, those alternatives include more efficient devices, greywater recycling systems and rainwater harvesting systems (RWHS) implementation, among others.

2.2. Rainwater harvesting

Rainwater harvesting systems have been implemented in countries such as Australia, Brazil and Japan, providing significant water savings.

These systems generally compromise a catchment area, a device that deflects the first portion of the water collected (first flush), a filter, a storage tank, an overflow unit, a supply system and piping, as schematized in Figure 1. The first flush rejection intends to avoid excessive contamination of stored water by diverting the most polluted waters.

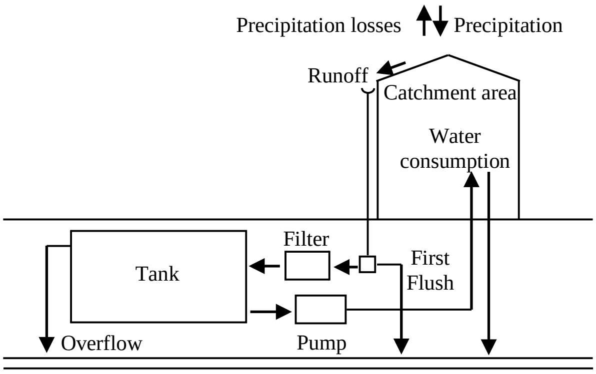

Figure 1 – RWHS components.

RWHS can be installed in new or existing building, and its design essentially consists in determining the storage tank volume which leads to greater water savings or least payback time. This determination can be made using various design methods that might be classified as empirical or analytical. Empirical methods include the Brazilian, German, English and Australian practical methods rely on variables such as precipitation, catchment area and water consumption to determine tank capacity in a very simple way, usually made through direct multiplications. Analytical methods explore the interaction between the system and the consumption pattern, in order to understand the system functioning. The Ripple method has the volume has unknown variable, and the Balance equations method simulates the system functioning in a daily basis, determining its associated efficiency.

3. Methodology

3.1. Technical evaluation

This work intended, in particular, to address the implementation of RWHS in commercial buildings. These type of buildings are usually characterized by large catchment areas and significant water consumptions in non-potable uses such as cooling towers, irrigation, fountains, cleaning services, among others, enhancing the potential for rainwater use.

It was selected the balance equations method (or simulation method), that consists in simulating a hypothetic RWHS has if it was already implemented. In order to explore several alternatives between consumption pattern, catchment area and tank size, it has been developed a technical evaluation tool in Matlab, which simulates the system on a daily basis. To do so, the tool relies on the following variables:

- **local precipitation** (mm) – it is recommended to use daily precipitation data from at least 10 years (Mitchell et al. 2008, ANQIP 2015);

- **catchment area** (m^2) – its value corresponds to the horizontal projection that is determined when consulting the architecture plants;

- **tank size** (m^3) – it is possible to select several tank sizes to be tested. It is recommended to pre-design the tank size using the consecutive days without rainfall method;

- **runoff coefficient** – varies according to the characteristics of the catchment area. In the case of impervious surfaces with little superficial retention, it is recommended to use 0.80 (ANQIP 2015);

- **first flush** (mm) – the technical specification 0701 (ANQIP 2015) suggests a value between 0 and 8 mm, recommending the usage of 2 mm when there is lack of further information;

- **total daily water consumption** (m^3/day) – should vary according to the month of the year, in order to take into account possible seasonal differences that might influence the results;

- **daily consumption of water for non-potable uses** (m^3/day) – amount of water which is intended for uses that that can be replaced by rainwater;

- **annual continuity** (yes/no) – simulation can be performed continuously or not. In the case of not being, the simulation starts every new year with an initial water volume corresponding to the next parameter;

- **tank fraction full at the beginning** – the simulation can be started with a certain initial water volume in the tank, which can vary between 0 and 1 (0 to 100 % of the tank capacity);

- **precipitation fraction before consumption** – simulates the daily temporal distribution of precipitation in relation to consumption. The value 0 is the most used storage algorithm, Yield After Spillage, which states that it does not rain before consumption. The value 1 corresponds to the inverse algorithm, Yield Before Spillage, for which it is assumed that 100% of the precipitation occurs before consumption (Jenkins et al. 1978 cited in Fewkes 2000).

Figure 2 represents the methodology underlying the technical evaluation.

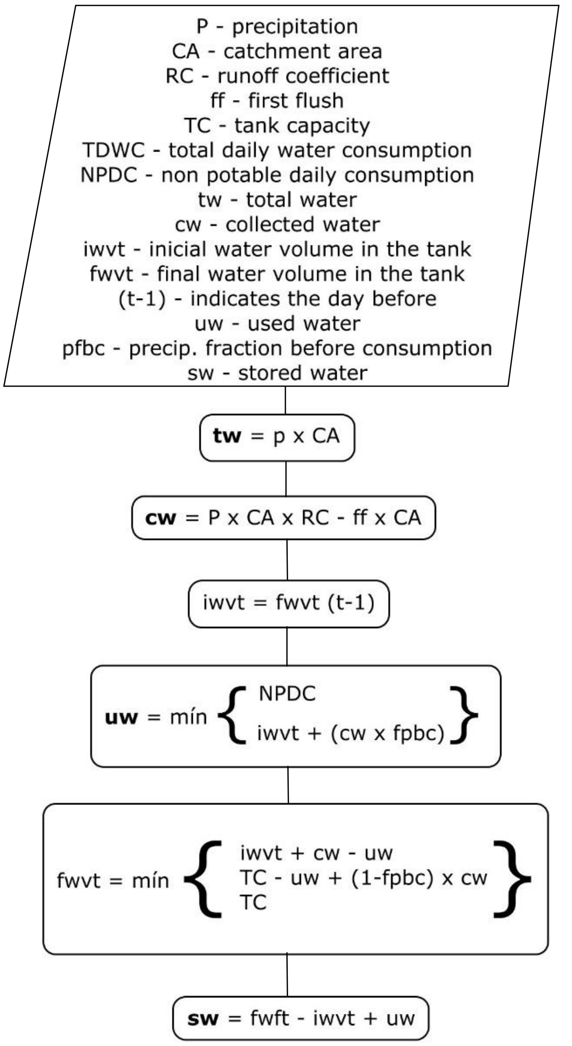

Figure 2 – Technical evaluation tool methodology.

It was considered that every day a certain amount of water is rejected, considering the minimum between the first flush value and the precipitation value. This is a highly conservative approach since there is no continuity for the first flush volume. It was also considered that there is no annual continuity, and that in the beginning of every year, the tank is empty (tank fraction at the beginning = 0). The results are later summarized into a set of annual indicators of the RWHS performance.

3.2. Economic viability

Solutions that provide higher savings correspond to larger tanks, which are associated with higher costs. Therefore, it is necessary to carry out an economic viability analysis to determine what solution will balance costs and benefits and allow an acceptable payback period. The analysis should take into account the following factors:

- **water savings** (m^3/year) – determined by the technical evaluation tool, esteems the rainwater quantity that is stored and utilized, and that therefore isn't bought to the public network;
- **water prices** (€/m^3) –allows to calculate the annual savings associated to each RWHS. Annual benefits are calculated through multiplying water savings for water price;
- **investment costs** (€) – should include network remodeling costs, tank construction/installation and the supply and installation of all necessary accessories;
- **operation and maintenance costs** (€/year) – includes pumping and maintenance. Maintenance periodicity is recommended in the technical specification 0701 (ANQIP 2015);
- **payback period** (years) – once the investment objective isn't direct profit, it was not considered any type of rate. Payback period is achieved when the summed cash flows (benefits minus operation and maintenance costs) equal the investment costs (I), so that:$\sum_{i=1}^{n} CF_i = I$.

4. Technical evaluation tool validation

It is expected that RWHS constitute an alternative water source to use in non-potable water ends, such as cooling towers, HVAC system, irrigation, fountains, cleaning services, among others.

Sonae Sierra is an international shopping center specialist that owns 46 shopping centers in 4 continents and 14 countries. This company has been demonstrating great environmental concerns and it has implemented RWHS in some of their shopping centers around the world.

4.1. Colombo Shopping Centre, Lisbon, PT

In 2011, Sonae Sierra installed a RWHS in Colombo Shopping Centre (CSC). It uses a 40000m^2 catchment area and it has a 150m^3 tank. The rainwater is used in cooling towers, whose annual consumption is about 70000m^3 of water. The system has been monitored between 2012 and 2014, and it was possible to determine that an average of 6500m^3 of rainwater was used per year, which is equivalent to about 9,4% of non-potable water savings.

It was performed, with the technical evaluation tool, the simulation of the real system installed, according to the consumption values registered from 2012 to 2014. It was used precipitation records from the same period from a monitoring station located in Cais do Sodré, Lisbon, at about 12 km from CCC.

The other adopted parameters correspond to: runoff coefficient = 0,8; first flush = 1mm, annual continuity: no; fraction of the full tank at the beginning = 0; precipitation fraction before consumption = 0. The tool estimated that the RWHS used about 6600m^3 of rainwater per year, which also corresponds to 9,4% non-potable water savings. This comparison validated the tool developed, ensuring its adequacy for the design of new RWHS.

4.2. Parametric analysis

Several performance indicators were considered to evaluate RWHS, giving particular emphasis to the efficiency (= stored rainwater/ collected rainwater) and non-potable water savings (= used rainwater/ non-potable consumption). It was analyzed the influence of some of the parameters involved, pointed in Table 1, through comparison of the standard situation with an alternative situation where each parameter is changed individually.

Table 1 – Parameters involved in the parametric analysis.

Parameter	Standard	Alternative
Precipitation values	Daily values	Average daily values
Consumption distribution	Monthly average	Annual average
Precipitation stations	Cais do Sodré	Caneças ; Point 174
First flush	1mm	2mm
Prec. fraction before cons.	0	0,5 ; 1

4.2.1. Precipitation Values

It was possible to conclude that using average daily precipitation values (average value of the precipitation in each day of the precipitation record series) tend to reduce the number of days in which there would be no rain at all. Consequently, there is an increase of the systems efficiency when compared to using the real daily precipitation data (Figure 3).

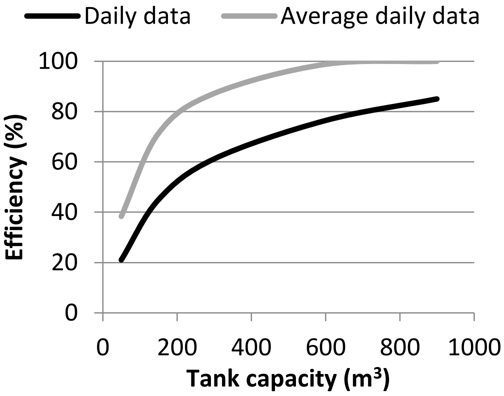

Figure 3 – RWHS efficiency according to precipitation data.

4.2.2. Consumption distribution

Consideration of daily consumption values determined for each month was compared to daily consumption value determined as an annual average. However, Colombo Shopping Centre has a much higher consumption than rainwater availability, so this question is not relevant.

4.2.3. Precipitation Stations

It was verified that different precipitation stations have great influence in the results, as illustrated in Figure 4.

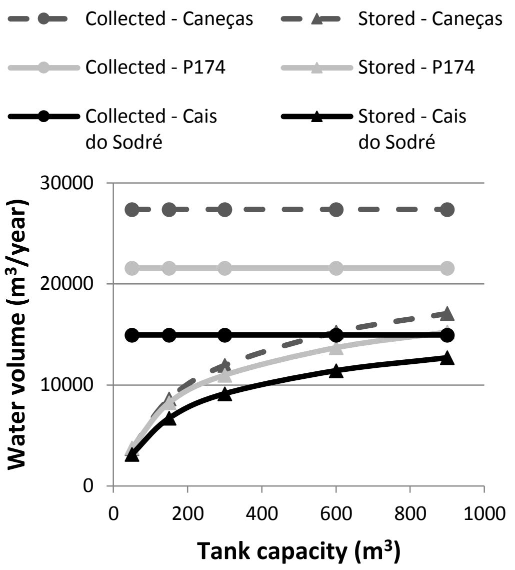

Figure 4 – Water volume variation according to precipitation station considered.

4.2.4. First Flush

First flush variation hasn't shown differences in the systems efficiency because that parameter evaluates the amount of used rainwater considering the collected rainwater, which already excludes first flush. Therefore, it is only possible to observe different non-potable savings, which directly depends on the amount of water used, which is lower for higher first flush values, as represented in Figure 5.

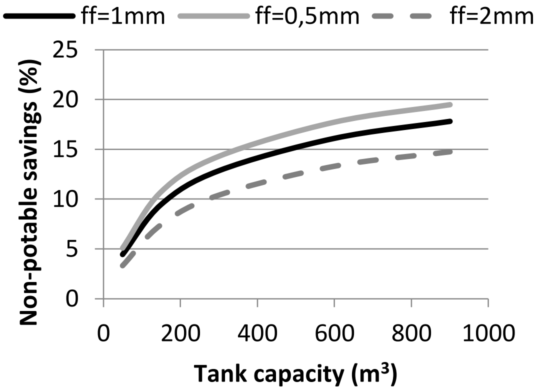

Figure 5 – Non-potable water savings according to considered first flush.

4.2.5. Precipitation fraction before consumption

Assuming that the entire precipitation occurs either before or after the consumption does not exactly correspond to reality. Intermediate values represent a more distributed sequence of events, which is expected to increase the systems efficiency. That has been observed during this work (Figure 6).

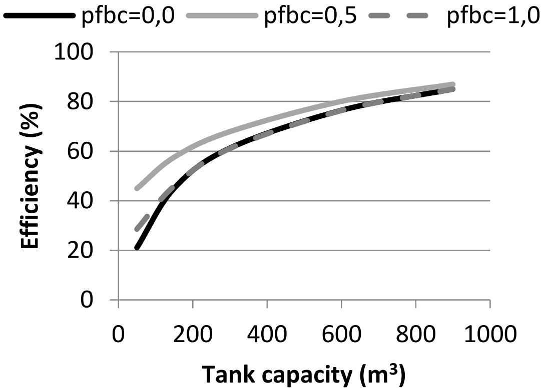

Figure 6 – Efficiency according to precipitation fraction before consumption.

5. Case studies

After validation, the technical evaluation tool was then applied in the RWHS's design of two Sonae Sierra's shopping centers.

5.1. Estação Viana Shopping, Viana do Castelo, PT

From the documents provided by Sonae Sierra, it was possible to select the two relevant catchment areas, A1 ($4280m^2$) and A2 ($9920m^2$) from Estação Viana Shopping (EVS). It was also possible to determine the water uses in the building, illustrated in Figure 7.

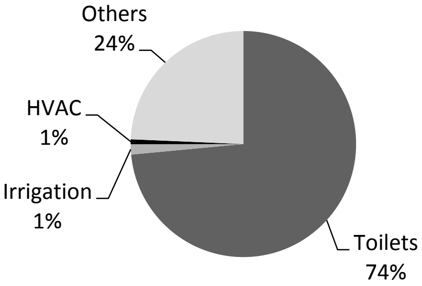

Figure 7 – EVS: water consumption in 2013, per use.

It wasn't possible to accurately determine what percentage in each use is designated to non-potable ends, so it has been considered that irrigation and HVAC were 100% non-potable uses. For the remaining consumption it was considered three different scenarios: C1, C2 e C3, corresponding to 50%, 70% and 90% of non-potable use. It was considered that C2 is the most likely to be similar to reality, resulting in about $7000m^3$ of non-potable water use per year.

The 57 years of precipitation data series used were obtained from Belo-Pereira et al. (2011). The precipitation was determined from two point located at about 11km north and south from EVS. The results in Figure 8 were calculated from the average of each precipitation point's value.

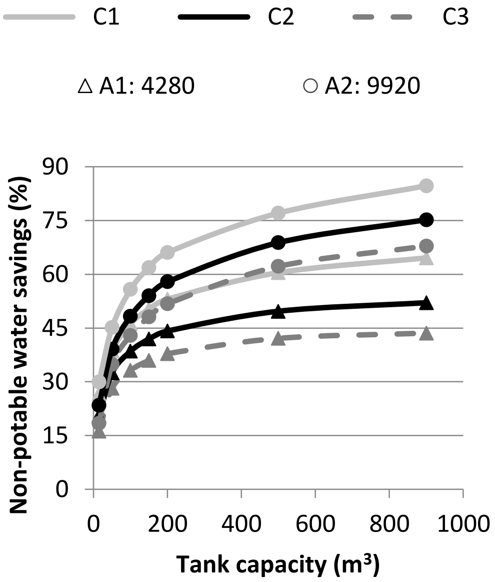

Figure 8 – EVS: Non-potable water savings.

It is possible to observe some stabilization around the $200m^3$ capacity, whereby the economic viability was studied for volumes 200, 300 and $400m^3$.

Budget from Colombo's RWHS was provided by Sonae Sierra and has been adapted to EVS. More detailed information was considered classified, but it was possible to identify that the annual operation and maintenance costs correspond to approximately 1,5% of the investment costs. Considering scenario C2 all costs involved, it was possible to calculate payback periods that vary between 46 years (smaller area, larger tank) and 25 years (larger area, smaller tank). This last was identified as the most favorable situation, with a 9920m^2 catchment area and a 200m^3 tank, allowing annual non-potable savings of almost 60%.

It is important to mention that water prices in Portugal are extremely low, when compared to other European countries, for example. A sensibility analysis was performed, allowing to observe that the payback period decreases almost linearly until -18% (less 4 years) and then it tends to stabilize (Figure 9).

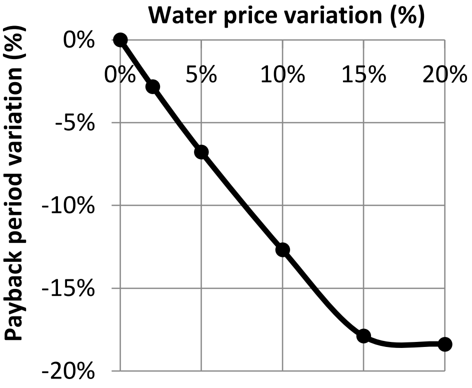

Figure 9 – EVS: Sensibility analysis.

5.2. Boavista Shopping, São Paulo, BR

It was possible to identify two catchment areas, B1 (4190m^2) e B2 (12240m^2). B1 corresponds to the non-accessible area and B2 includes also the parking lot in the roof. The use of the parking lot as catchment area implies the installation of a hydrocarbon retention camera upstream of the reservoir. After studying the consumption information provided by Sonae Sierra, it was possible to determine the Boavista Shopping (BS) consumption patter (Figure 10).

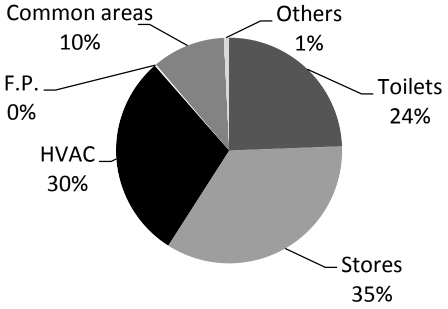

Figure 10 – BS: water consumption in 2013, per use.

Its uses are divided in toilets, stores, HVAC system, firefighting and common areas. It was possible to identify that about 22500m^3 of water are annually used in non-potable consumptions, and can be, therefore, replaced with rainwater.

Precipitation data from the Astronomical and Geophysical Institute of the University of São Paulo and from the São Paulo/SP – Mirante de Santana meteorological station were used. The first is located at about 11km from the shopping center, and the second one is located at about 19km, so the presented results in Figure 11 correspond to a 2/3 and 1/3 weighting.

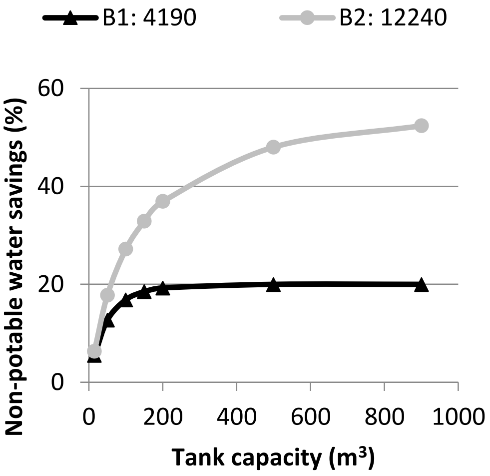

Figure 11 – BS: Non-potable water savings.

It is possible to observe that results from area B1 tend to stabilize around the 100m^3 capacity, whereby the economic viability was studied for volumes 100, 150 and 200m^3. However, there is no evident stabilization regarding the B2 area results, so it was considered adequate to study the 200, 300 and 400m^3 volumes.

The required construction works were based in the Portuguese case studies budgets, along with price adaptation to the Brazilian market. After estimating investment costs, it was considered that operation and maintenance costs represented 2% of the investment costs. Although the involved values were considered classified, the investment options allow 20-50% non-potable water savings, and payback periods under two years.

Differences between Portuguese and Brazilian case studies existed due to the fact that construction materials and labor are more expensive in Portugal, and water (and sanitation) fees are higher in Brazil.

6. Conclusions

This work aims to contribute to water efficiency promotion in commercial buildings. Rainwater harvesting system implementation in commercial buildings such as shopping centers implies not only economic and environmental advantages, but also not measurable advantages, when taking into account how the "green" component of a business may impact their image to the consumers.

It was developed a technical evaluation tool that simulates hypothetical systems on a daily basis, considering factors such as local precipitation, catchment area, roof material, tank capacity, consumption patter, runoff coefficient, first flush height, precipitation fraction before consumption, among others.

The tool was then validated after comparing the 9,4% real non-potable water savings monitored in Colombo Shopping Centre's RWHS with the 9,4% non-potable water savings estimated by the technical evaluation tool. After validation, the tool was used in the RWHS design for two Sonae Sierra's case studies.

The first case-study is located in Viana do Castelo, Portugal. Two catchment areas were studied, considering three distinct consumption patterns and several tank capacities. One of the consumption patterns was considered has being the most similar one with reality, and to that pattern it was advised a 200m^3 tank installation, regardless of the selected catchment area. It's installation in the smaller area (4280m^2) leads to a 43 years payback period, and in the smaller area (9920m^2) it leads to a 25 years payback period. The low Portuguese water rates are responsible for such high payback period values. A sensibility analysis was performed, showing that the payback period can be reduced in 18% if the water rates would increase that much.

The second case-study is located in São Paulo, Brazil, were two catchment areas were studied. For the 4190m^2 area were advised 100 to 200m^3 tanks, and for the 12240m^2 area were advised 200 to 400m^3 tanks. All studied investment options led to payback periods under two years. Differences between Portuguese and Brazilian case studies were so evident due to higher investment costs in Portugal contrasting with higher water rates in Brazil.

Although RWHS present several advantages to the company that decides to implement them, it's important to retain some important conclusions. Even when design parameters are carefully selected, that doesn't implies that simulation results can predict the future system's performance. The evaluation tool estimates its results based in historical precipitation data, and therefore it is expected that the estimated results are as closer to reality results as the historical data precipitation is to the real precipitation. Climate changes experienced nowadays are a consequence of the past, and will most certainly have impact on the future. It is recommended that future works study those changes in order to understand its impacts on precipitation, which directly affects the rainwater harvesting systems design. Correct designs lead to implementation increase around the globe, and consequently to a more sustainable world.

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