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Rainwater Harvesting System for Industrial Buildings: The Case Study of Continental Advanced Antenna, Vila Real, Portugal

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Abstract: Large industrial units generally consume considerable volumes of water for use by workers and sometimes in the manufacturing process, but on the other hand, they generally have large coverage areas that facilitate and enable the capture of large quantities of rainwater. Rainwater harvesting systems (RWHSs) are an alternative water supply with high potential for significant water and economic savings in buildings of this type, also with benefits for water resource sustainability. This paper presents a case study that refers to the design and economic viability determination of an RWHS to be installed in the industrial building of *Continental Advanced Antenna Portugal*, using an innovative tool called SAPRA—a rainwater harvesting and greywater reuse system in buildings. The main goal was to understand water consumption patterns in social areas (common to most of the industrial typologies) and determine whether RWHSs are feasible in such uses (discarding the production chain). The case study allowed for verification that the assumptions regarding the calculation period design flow significantly interfere with the design flow and the storage capacity. The analysis of the 10-year period yields the most realistic results, and can be framed, if necessary, within the range provided by the analysis of the driest and wettest years. The investment costs should between EUR 90 and 95 million, with annual savings of EUR 7 to 12 million, respectively. The expected payback period is between 7 and 11 years, which is quite feasible and very relevant. This may be an excellent example of how, even within the industries that do not need water for production, this may save significant volumes of water, contributing to the efficient use of this valuable resource.

Keywords: rainwater; harvesting; SAPRA; industrial building

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1. Introduction

The non-sustainable propensity of increasing surface and groundwater extraction to satisfy the increasing demand of water is a reality, and some changes must be made in order to increase the efficient use of this valuable resource [1]. Efficient water consumption requires a multifaceted approach that includes technological advancements, behavioral changes, policy adjustments, and infrastructure improvements.

Rainwater harvesting systems (RWHSs) are an alternative water supply system that reduces the burden on water resources and, consequently, minimizes the ecological footprint through potable water [2–5]. These systems are indeed presented as an alternative water to be included in urban water cycle management and are being implemented in areas with very different rainfall patterns, such as Jordan [6], India [7], South Africa [8], Brazil [9], the USA [10], Australia [11], and the UK [12].

The core benefits related to RWHSs include flood risk reduction due to reduced urban runoff [13]; autonomy and diminished dependency on distant water sources, reducing a city's external water request and improving water stress on the area by indorsing significant potable water savings; decreasing stormwater streams treated in wastewater treatment plants (WWTP); and decreasing diffuse water pollution [11,14–19].

Commercial RHWSs generally collect large amounts of rainwater and utilize collected water in various ways. In fact, RWHSs can help industries conserve millions of liters of water over the lifetime of the system, impacting on their economic savings as well. By using large-scale RWHSs, industries can manage stormwater runoff from their impervious areas, directing this water to other purposes. RWHSs are not just an environmentally friendly action but could also have several additional benefits as well, such as irrigation, stormwater management in countries with abundant water resources once the load on urban drainage systems during intense precipitation is reduced [20], fire suppression, cooling towers, vehicle and equipment washing, laundry, and toilet flushing.

Water conservation efforts are receiving heightened attention, and industries that choose to implement commercial RWHSs not only help in that struggle but can also save businesses money. In fact, implementing RWHSs can reduce reliance on municipal water supplies, leading to lower water bills. It also helps mitigate the impact of water scarcity, ensuring a more sustainable water supply for industrial operations. By collecting and utilizing rainwater, businesses can reduce their environmental footprint, enhance their corporate social responsibility profiles, and potentially gain tax incentives or rebates offered by local governments for sustainable practices.

RWH systems are usually integrated into the building design, and are classified as decentralized systems, allowing for the gathering of rainwater and its treatment from rooftops and downspouts [19,21]. An RWHS generally contains a catchment area (generally the roof area), a screen, a storage tank, a supply network, pipes, and an overflow unit [22,23]. Operational efficiency is affected by several parameters in terms of economic feasibility, namely, the amount of rainfall, the catchment area, the storage tank volume, the water-use demand, and the effectiveness of runoff collection and the filter [23].

Results from previous studies show the feasibility of RWHSs. For example, Imteaz et al. (2012) [24] quantified that an individual building with a 150 m^2 rooftop area and 1–5 m^3 tank in Sydney can save 10–58% water, depending on the number of people in the house. In Sweden, 30% water savings can be attained from an RWHS using a 40 m^3 tank to supply the toilet and washing machine [16]. Ghisi et al. (2007, 2009) [9,25] achieved 12–79% savings per year of drinkable water when they investigated a rainwater-harvesting system in several cities in Brazil. In regional Victoria in Australia, Muthukumaran et al. (2011) [26] found out that the use of rainwater inside a home can save up to 40% of drinkable water. Ward et al. (2010) [27] stated that RWHSs can replace 36% to 46% of water used in toilets, resulting in payback periods of 23 and 7 years, respectively. When monitoring the performance of an RWHS in a supermarket, Chilton et al. (2000) [28] concluded that about 41% of the demand for toilets and urinals could be provided by rainwater.

Rainwater harvesting systems for industrial buildings have been the subject of quite a few international studies, already referenced, generally aimed at evaluating their feasibility, effectiveness, and potential benefits. There is an absence of information regarding the performance of RWHSs in industrial buildings, which can be major water consumers in urban areas, and this is the main, novel approach of this paper.

This paper presents a case study that refers to the design and economic viability determination of an RWHS to be installed in the industrial building of Continental Advanced Antenna Portugal using an innovative tool called SAPRA—a rainwater harvesting and greywater reuse system in buildings. The main goal was to understand water consumption patterns in social areas (common to most of the industrial typologies) and understand whether RWHSs are feasible for such uses (discarding the production chain).

2. Case Study

The case study was developed in Continental Advanced Antenna Portugal, which is an industrial installation located in Vila Real, Portugal, where water is only used in the social area. This company is one of the main specialists and manufacturers of antennas for vehicles in Europe. The company's facilities have five floors, four of which have utilities that use water, such as bathrooms, canteens/bars, changing rooms, cleaning taps, and washbasins. The rooftop (Figure 1) is 2765 m^2 and is an excellent surface to recover rainwater for non-potable uses.

Figure 1. Case study of Continental Advanced Antenna Portugal.

Several non-potable end uses for RW were evaluated, such as toilet/urinal flushing (which can be one of the largest uses of water in a large office building), cooling towers, carwashes, automated fire suppression systems, boiler systems and thermal HVAC systems, and irrigation of green spaces. RW can be a valuable resource to supplement or replace the use of potable water in such uses. However, for this particular case, only irrigation was considered, as the other end-uses would require extensive construction efforts and investments. The flow chart of the considered RWHS is presented in Figure 2.

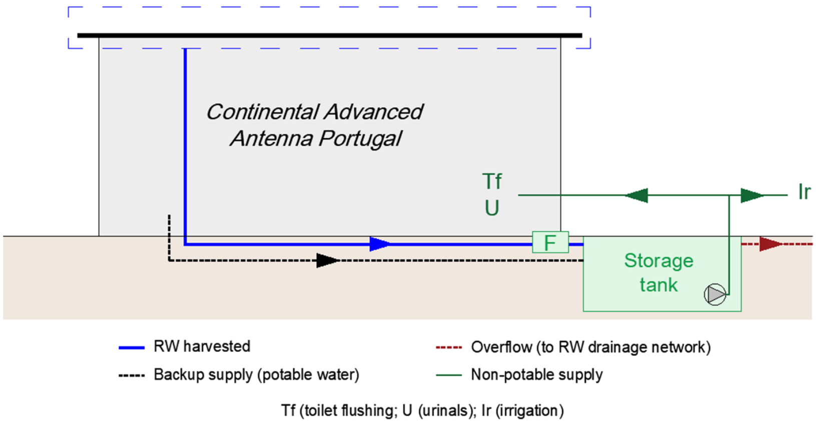

Figure 2. Schematic representation of the rainwater harvesting system considered for Continental Advanced Antenna Portugal.

3. Methods

3.1. Decision Support Tool: SAPRA

A decision support tool called SAPRA, developed by Santos (2012) [29] using Microsoft Office Excel 2007 and programmed in Microsoft Visual Basic for Applications (VBA), was used to carry out the performance simulations for this study. This program allows for the volume of the rainwater storage tank to be determined, conducts a performance analysis of the RWHS with the defined volume, and carries out an economic study that yields the payback period of the investment. Further details about the program's functioning and structure can be found in Ferreira et al. (2023) [30].

The analysis was carried out for different scenarios in which distinct tank volumes are subject to a daily performance analysis, considering a yield-before-spillage (YBS) approach. At the end of each day, the volume of rainwater that came from the previous day, the volume of rainwater of that day, and the respective non-potable consumption are analyzed. The program considers the existence of a back-up supply that provides potable water to the system, if needed.

Information related to the location of the building, the equipment to be supplied with non-potable water, the characteristics of the RWHS to be implemented, and the unitary installation costs were introduced in the program. The current characteristics of the building and information about employees were collected from visits to the factory and from analysis of the provided documentation. Therefore, the following input data were considered:

- Number of occupants: 535;
- Non-potable uses to be supplied: 33 flush toilets, 10 urinals, 8957 m^2 of green area (mixture of trees/shrubs) to be irrigated by sprinkler from May to September;
- Rainwater collection area: 2765 m^2 (impermeable cover);
- Type of treatment to be applied to the collected water: filtration;
- Extension of the drainage network to the reservoir: 285.2 m (PPc);
- Characteristics of the non-potable water-pumping group: 50 mwc of head and 2.5 L/s of pumped flow;
- Supply network; 256 m for toilets, an extra 12 m for urinals (tricomposite pipe), and 300 m for irrigation (PVC);
- Estimated annual maintenance cost in relation to the system installation cost: 1%;
- Admitted supply tariff: AdiN (a company that manages water supply in Vila Real), 2022;
- Precipitation records used: from 2010 to 2022.

In addition, some default information presented by the program was used, such as capitation and distribution of consumption, types of coverage and irrigation needs, treatment costs, material and equipment costs, and precipitation records.

With all the basic information inserted into the program, it was possible to calculate the tank volume and to simulate the performance of the system, as presented in Figure 3.

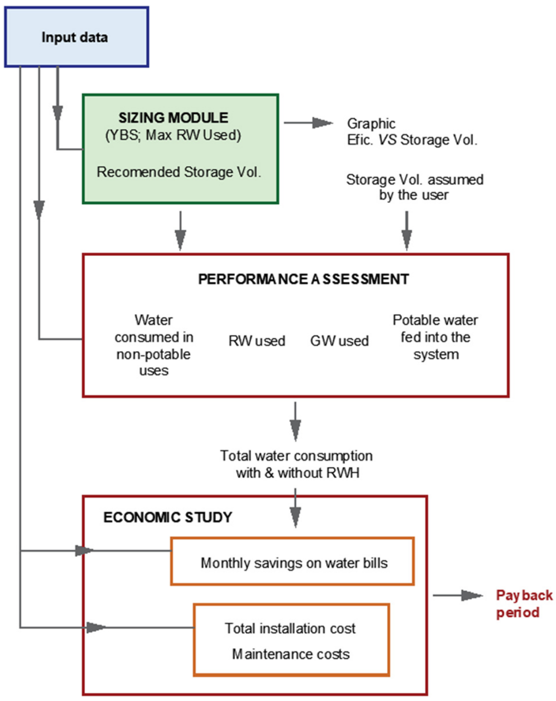

Figure 3. Schematic representation of the program's operation.

3.1.1. Precipitation Data

SAPRA performed a performance simulation for a 10-year period, using precipitation data collected from the National Water Resources Information System (SNIRH—Portugal), considering the meteorological station in the study area. Collected data covered the years between 2010 and 2020. Taking advantage of the program's potential to provide a comprehensive study of different climatic scenarios, a simulation of a single year (the average year, in terms of precipitation), the three driest years (pessimistic perspective), and the three wettest years (optimistic perspective) was also completed, considering the referred precipitation period.

3.1.2. Non-Potable Consumption of the Collected Water

The method used by SAPRA to determine the size of the tank volume was the maximum rainwater use method, which resulted in the maximum tank volume above, which indicated no increase in the amount of rainwater consumed. The calculation was based on a YBS balance between the daily volume of rainwater produced and water consumed for non-potable purposes. It could have been considered YAS (yield-after-spillage), but this is more penalizing than YBS in the sense that consumption is limited to the reserve volume, and a possible surplus of RW is rejected before the water is consumed throughout the day. Since this industrial building has a continuous daily use in the social areas (with water consumption during rain), YBS was admitted.

Daily rainwater collected (V_RW) was obtained from the precipitation data considering Equation (1):

$$V\_RW = P \times A \times C \times \eta_f \tag{1}$$

P—daily precipitation (mm);
A—catchment area (m^2);
C—runoff coefficient;
η_f—hydraulic efficiency of the filtration treatment

Predefined values for the runoff coefficient were used after consulting ANQIP (National Association for the Quality of Building Installations), which recommends values of between 0.7 and 0.9 for impermeable surfaces [31]. For this study, the average value (0.8) was admitted. Since this case is an industrial building and the rainwater harvesting area is quite high, compared, for example, to a residential building, the volume of water wasted in washing the filters was considered insignificant, so the filtration efficiency in this case was close to 1.0.

The non-potable water uses considered for this case were toilet flushing/urinals and garden irrigation, resulting in the total volume defined by Equation (2):

$$V\_(non\text{-}potable\ water\ required) = V\_(Tf/U) + V\_Ir \tag{2}$$

V_(Tf/U)—volume of non-potable water required for use in toilet/urinal flushing;
V_Ir—volume of non-potable water required for garden irrigation;

Non-potable water volume for toilet/urinal flushing was determined considering the number of occupants and the corresponding capitation. For garden irrigation, the area of the gardens and the irrigation needs (for the corresponding type of grass) were considered.

An emergency supply from the building's potable network was considered for the days where the volume of water consumed is higher thar rainwater produced in the RWHS.

3.1.3. Performance Analysis

SAPRA conducts the performance analysis on a daily base for several storage volumes and presents a tank size that would not produce an increase of more than 0.1 m^3 of rainwater consumed in non-potable uses. This is referred to as the application of the maximum rainwater use method, which results in a constant value for the minimum storage volume from which there is no increase in the volume of rainwater used and the cumulative water savings approach [32,33].

After presenting the recommended storage volume, SAPRA allows the user to introduce a different one (if, for example, the recommended value is too big for the available installation area) and starts a new performance analysis. In parallel, the program also presents the efficiency of the system for all the storage volumes used in the sizing process, which helps in the decision-making process. This efficiency is obtained by the ratio between the volume of non-potable water used and the volume of non-potable water required for the final uses considered.

3.1.4. Economic Study

The economic study conducted by SAPRA determines the monthly savings by applying the tariffs of the municipality to the average global consumption and to the reduced average global consumption each month. This way, the cost of the water bill for the building without the RWHS and with the RWHS is obtained, and the difference between them is the monthly savings.

Comparing these savings with the installation and maintenance costs allows the program to present the estimated payback period. To do so, all costs involved in the execution of the project are considered investment costs. The maintenance cost is estimated by applying a maintenance percentage to the investment cost. Then, the investment payback period is determined, defined as the time interval (in years) necessary for savings to compensate for the initial investment made. In the year in which operation begins, the installation cost is an expense and there are no savings. After that point, a balance between the investment costs and the successive annual maintenance costs is achieved with successive annual savings. The year in which the savings exceed the expenses corresponds to the desired payback period. The energy costs associated with the operation of the pumping group are not considered, nor is an increase in the cost of water that may occur in the future.

4. Results and Discussion

The study considered four precipitation scenarios. In the first one, the analysis was carried out for a period of 10 years, considering the precipitation recorded at the location from 2010 to 2020. In the second and third scenarios, the process was carried out for the three driest and wettest years, respectively, of that period. In the fourth scenario, the dimensioning was presented considering the average year of precipitation also recorded in that period. Table 1 summarizes the results obtained.

Table 1. Sizing results of the rainwater-harvesting system.

	Scenario	10 Years	3 Driest	3 Wettest	Average Year
Performance analysis	Tank vol. (m^3)	330	160	315	260
	Average volume of water consumed in non-potable purposes (m^3/year)	9607.5	9607.5	9607.5	9607.5
	Used rainwater volume (m^3/year)	1969.4	1275.9	2587.7	2732.9
	Average volume of drinking water fed into the system (m^3/year)	7605.1	8278.3	6914.8	6789.3
Economic analysis	Estimated installation cost (EUR/year)	EUR 94,146.94	EUR 79,066.51	EUR 92,944.02	EUR 88,358.19
	Maintenance costs (EUR/year)	EUR 941.47	EUR 790.67	EUR 929.44	EUR 883.58
	Average savings on drinking water not consumed (EUR/year)	EUR 8794.33	EUR 5837.74	EUR 11,825.85	EUR 12,376.90
	Return on investment (years)	11	15	8	7

The results show that an analysis based on drier years resulted in the lowest tank volumes, due to less RW available to manage. Conversely, an analysis of the wettest years resulted in tank volumes slightly lower than in the analysis for the 10 years of rainfall records and higher volumes of used RW. This indicates that higher abundance in the influent water also results in lower needs for regularization and more optimistic results.

The average monthly volume of rainwater used was quite variable, and the patterns were different for each studied scenario (Figure 4). Considering the most complete analysis, for 10 continuous years, the pattern increased from October to January, where the highest value was verified, and then decreased until the summer months (in July and August the volume of rainwater used was minimal). This shows the predominance of rainfall in the winter months throughout the decade under analysis, which was confirmed by the analysis for the wettest years, in which the pattern was similar, although with some alternations during the winter.

On the other hand, upon analyzing only an average year, there was a peak in the use in September and minimum values in June and July. This pattern is not representative, as it only reflects the monthly change in rainfall for a given year, where the total volume of precipitation is an average value of the 10 years of records.

After analyzing the average monthly variation in the volume of drinking water that had to be fed into the systems (Figure 5), the highest values were found in the summer months, as would be expected. However, the analysis for the three driest years revealed little variation, with December and February being the months where it was necessary to insert less drinking water because they were months where rainfall was higher and where irrigation needs were null.

The variation in the average monthly savings was influenced by the volume of rainwater used and the drinking water inserted into the system. Figure 6 shows typical patterns of the driest and wettest seasons in the 10-year analysis. This pattern was totally different for an analysis of only one year, even though it was a year of average rainfall. As can be seen, one of the winter months was one of those with the lowest financial savings, due to the atypical fact that in that year there was very little rain in that month. Comparing the monthly savings from a more pessimistic scenario (3 driest) to a more optimistic one (3 wettest), the difference in the order of magnitude of the values stands out. Also, there was a significant monthly variation between high savings in March (about EUR 2270) and practically zero savings in August, which reflects, once again, the concentration of rainfall in the winter months.

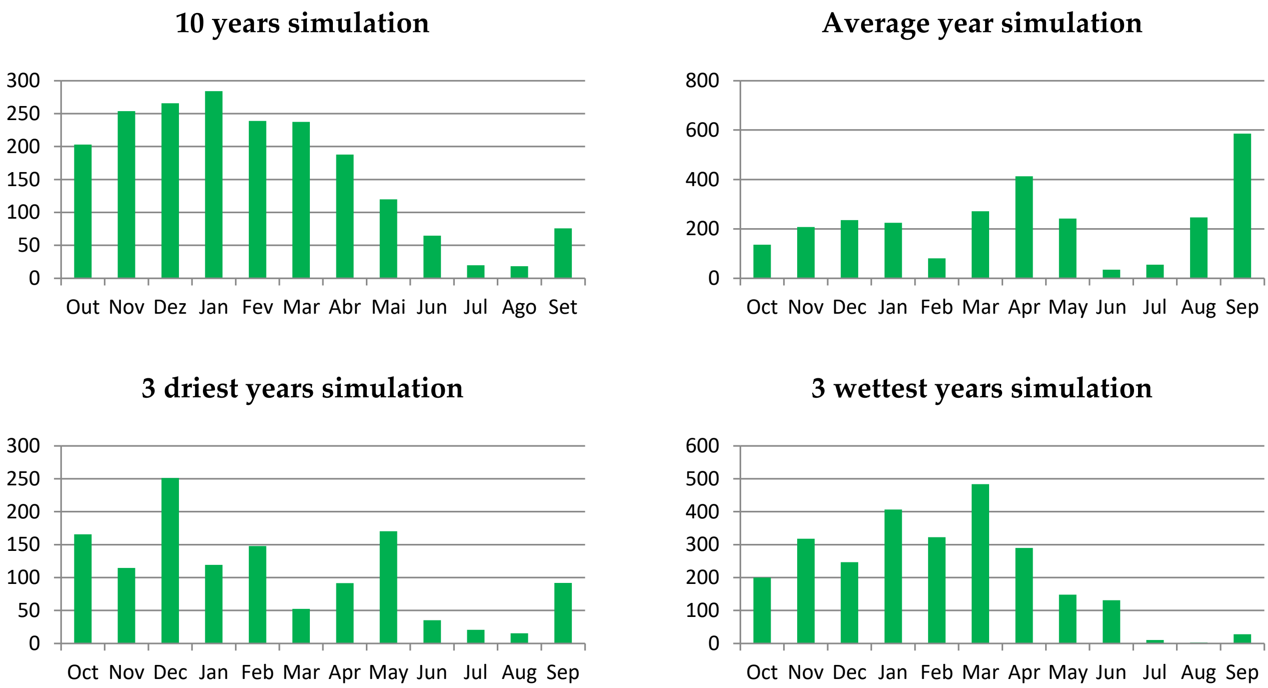

Figure 4. Used rainwater volume (m^3/month).

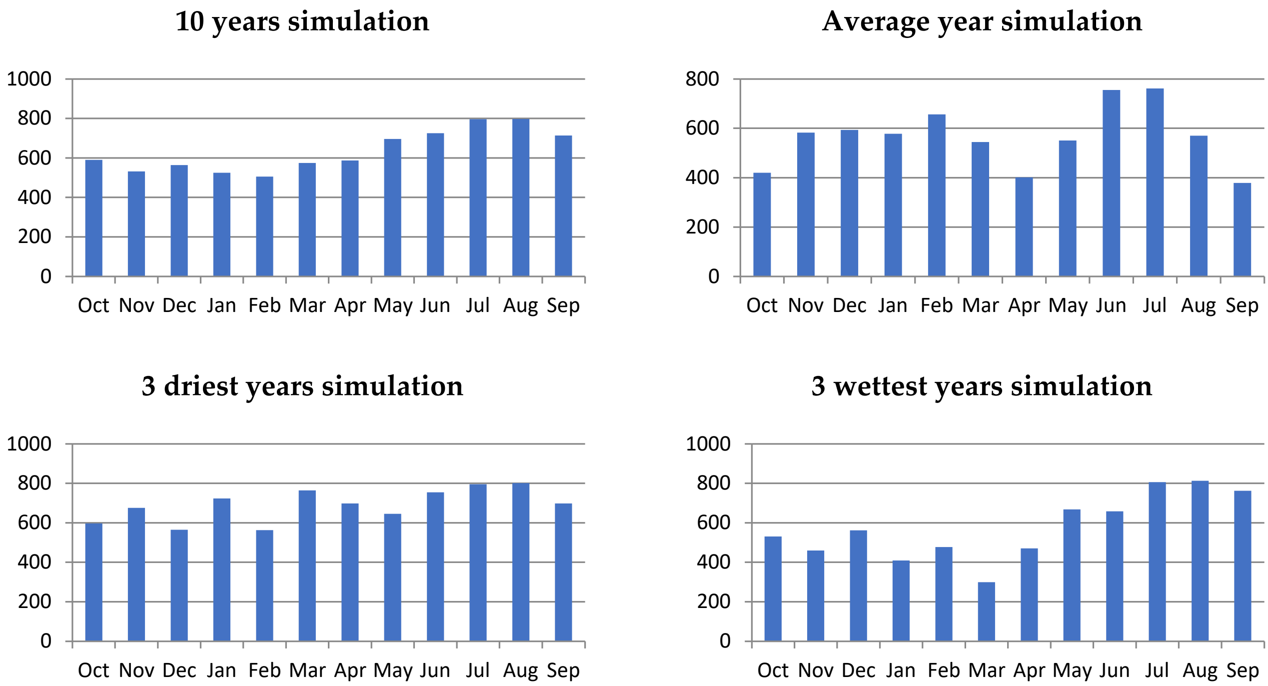

Figure 5. Average volume of drinking water fed into the system (m^3/month).

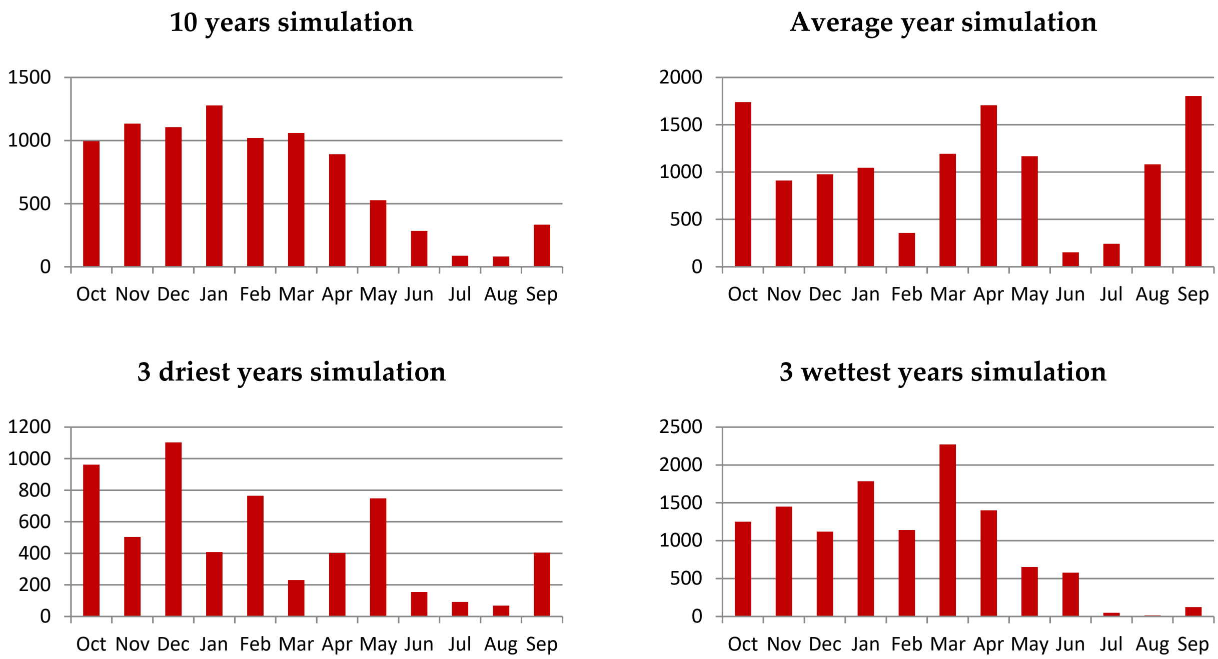

Figure 6. Average savings on water bills (EUR/month).

In general, for this industrial building, the recommended tank volume was between 160 and 330 m^3, but the value of 160 should not be considered because it corresponds to a rather pessimistic analysis (3 driest years), therefore resulting in little water to regulate and lower annual savings. Thus, excluding those values, it can be seen that the investment would be between EUR 90 and 95 million, with annual savings of EUR7 to 12 million, respectively. The expected payback period would be between 7 and 11 years, which is quite feasible and supports the decision to build the system.

It should be noted that this study only took into account the use of RW in social areas and not in the production chain, indicating that the use of rainwater in industries is feasible and should be promoted, even if there is no significant consumption in the industrial process.

5. Conclusions and Further Remarks

A more sustainable use of water implies a more rational use of water from the public water supply systems, which is generally very expensive due the costs of the treatment process and the costs of energy consumption in transport.

Rainwater is a good alternative source to public water, given its quality, which allows for safe use for non-potable purposes.

The main problem with the use of rainwater is related to its temporal variability, depending largely on the climate, which can imply appreciable storage volumes, with reservoirs representing the biggest cost in in rainwater-harvesting systems.

Large industrial units generally consume considerable volumes of water for use by workers and sometimes in the manufacturing process, but on the other hand, they generally have large coverage areas that facilitate and enable the capture of large quantities of rainwater.

The case study presented verified that the assumptions regarding the calculation period significantly interfere with the design flow and the storage capacity. Analysis based on drier years resulted in the lowest tank volumes, due to less RW available to manage. Higher abundance in the influent water resulted in lower needs for regularization and in more optimistic results. Patterns of the driest and wettest seasons in the 10-year analysis were totally different for an analysis of only one year, even though it was a year of average rainfall. This reveals that the calculation and analysis of RWHS systems in industrial buildings should avoid average years. The analysis for the 10-year period is the one that will yield the most realistic results and can be framed, if necessary, within the range provided by the analysis of the driest and wettest years.

It must be considered that, in Portugal, summers are very dry and long and, therefore, the use of rainwater for irrigation is not the most suitable alternative. It is preferable to use it only for domestic or industrial purposes and preferably in months when there is precipitation, which significantly reduces the required reservoir capacity. Even so, in this case study, which has an appreciable green area, the return-on-investment time is quite appealing.

It can also be concluded that the investment costs should between EUR 90 and 95 million, with annual savings of EUR 7 to 12 million, respectively. The expected payback period is between 7 and 11 years, which is quite feasible and very relevant.

In summary, the main advantages of the installation of such a system include:

- Water conservation: Rainwater harvesting reduces reliance on freshwater sources, conserving water resources and reducing the environmental impact of water extraction.
- Cost savings: By using harvested rainwater for non-potable purposes such as irrigation, cooling, or toilet flushing, industrial facilities can reduce their water bills and operational expenses.
- Stormwater management: Rainwater harvesting helps to mitigate stormwater runoff and reduce the risk of flooding and erosion in industrial areas by capturing and storing rainwater onsite.
- Sustainability: Implementing a rainwater harvesting system aligns with sustainability goals and demonstrates a commitment to environmental stewardship and resource efficiency.
- Resilience: Having an alternative water source can enhance the resilience of industrial operations by providing a backup supply during water shortages or emergencies.

Overall, a well-designed rainwater-harvesting system can be a valuable investment for industrial buildings, offering both environmental and economic benefits while supporting sustainable water management practices.

It can therefore be noted that the use of rainwater in industrial units is a feasible solution for preserving water and upholding environmental and economic sustainability.

This may be an excellent example of how, even within the industries that do not need water for production, they could save significant volumes of water, contributing to the efficient use of this valuable resource.

Author Contributions: All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by C.M. and C.S., and both performed the work structure, editing, and revisions. The first draft of the manuscript was written by C.M., and all authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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