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The Feasibility of Rainwater Harvesting Systems in Buildings with Green Roofs: A Case Study Based on the Köppen Climate Classification

Carla Pimentel-Rodrigues [1,2,3,*] and Armando Silva-Afonso [2,3]

1 Institute of Information Sciences and Administration (ISCIA), 3810-488 Aveiro, Portugal
2 National Association for Quality in Buildings Services (ANQIP), 3810-193 Aveiro, Portugal; asilva.afonso@outlook.pt
3 RISCO—Research Center for Risks and Sustainability in Construction, University of Aveiro (Portugal), 3810-193 Aveiro, Portugal
* Correspondence: anqip@anqip.pt; Tel.: +351-234-092-597

Abstract: The construction of green roofs (GR) combined with rainwater harvesting systems (RWHSs) in buildings can increase the advantages of each of these technologies, being a very promising solution to combat climate change and increase the sustainability of cities. However, the viability of this joint solution significantly depends on local climatic conditions. The planet's climate classification, known as the Köppen climate classification, is one of the most widely used climate classification systems. The Köppen climate classification divides climates into five main climate groups, with each group being referenced based on seasonal precipitation and temperature patterns. In the specific case of mainland Portugal, according to the Köppen classification, the climate is divided into two regions. In this article, case studies are developed for two Portuguese climatic regions, seeking to demonstrate the possibility of using the Köppen classification as a decision criterion for the eventual inclusion of rainwater harvesting systems in buildings with green roofs. For this study, the results of a previous study were applied, through which we obtained an expression to determine the runoff coefficients of green roofs common in Portugal, concluding that the Köppen climate classification can be used as a prior decision criterion regarding its incorporation or exclusion in rainwater harvesting system buildings combined with green roofs, depending on the location.

Keywords: climate change; green roofs; rainwater harvesting systems in buildings; Köppen climate classification

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1. Introduction

The effects of climate change on urban environments are already significant, but the intensity and frequency of heavy rainfall and heat waves is expected to continue to increase in the coming decades [1]. There will be an obvious increase in the risk of flooding, as well as a worsening of water stress or even water scarcity in many regions of the planet. Some countries may face, in the short/medium term, serious consequences of these impacts in a significant area of their territory [2].

In urban environments, the use of green roofs (GR) is a constructive solution that contributes to a greater resilience of cities in the face of some of these effects. The environmental benefits of GR on buildings are broad and well-known and include [3–10] the following:

(a) Increase in energy efficiency and a reduction in energy costs (by significantly increasing thermal insulation, reducing the thermal action of solar rays, reducing air conditioning needs in buildings, etc.);
(b) Improvements in the microclimate;
(c) Increase in photosynthetic activity, implying increased oxygen production, greater recycling of carbon dioxide, reduction of the greenhouse effect, etc.;

(d) Reduction in the heat island effect;
(e) Increased noise protection;
(f) Offer a natural habitat, allowing an increase in biodiversity and ecological niches;
(g) Replacement of lost landscape areas;
(h) Significant increase in green area in an urban context and a reduction in the negative impact of the massification of structures built in urban areas;
(i) Absorption/filtering of polluting gases and suspended particles from the atmosphere (toxic dust);
(j) Fire risk prevention (floristic compositions that include succulent plants slow the spread of fire);
(k) Retention of rainwater and dampening precipitation peaks, reducing the risk of flooding in urban areas.

The rainwater harvesting systems (RWHSs) in buildings are also suitable for dealing with the various impacts of climate change because, in addition to reducing flood peaks in urban areas, they promote additional water storage in buildings, contributing to the mitigation of problems arising from droughts [11–14]. With regard to the reduction in runoff due to the installation of RHWS, the literature shows a wide variation in results, but the reductions referred to in the literature are always very significant. A comparative study published in 2020 [15] reports minimum reductions of 9 to 12% obtained in the research in South Korea [16] and a maximum decrease in the runoff value of 44% in South Africa [17]. In China, Nanjing, a decrease of 57.7% was obtained for critical rainfall [18].

The construction of GR combined with rainwater harvesting systems (RWHSs) in construction brings together the individual advantages of each of these technologies, especially with regard to rainwater retention and dampening flood peaks in urban areas [19–25]; therefore, their combination should be considered as a very promising solution for tackling climate change and increasing the sustainability of cities [26–36]. However, the viability of this joint solution significantly depends on local climatic conditions; thus, it is of interest to pre-analyze the regions of the planet where the combination of GR with RHWS may or may not be viable [37–42].

One of the most widely used climate classification systems for the planet is the Köppen classification, published in 1884 by the German/Russian Wladimir Köppen [43]. Over time, this classification was improved by Köppen himself and also by climatologist Rudolf Geiger, which is why the system is generally called the Köppen–Geiger climate classification.

In the mid-1960s, the Köppen climate classification system was modified within the Trewartha climate classification system, and was further revised in 1980. The Trewartha system sought to redefine mid-latitudes to be closer to vegetation zoning and genetic climate systems.

The Köppen climate classification considers five main climate groups, with each group referenced based on seasonal precipitation and temperature patterns. The five main groups are A (tropical), B (arid), C (temperate), D (continental), and E (polar). All climates, except those in group E, have a seasonal precipitation subgroup, also represented by letters [44–46].

With climate change, the Köppen classification undergoes adjustments. Figure 1 shows a map with the Köppen climate classification for the period from 1980 to 2016 [45].

It is interesting to analyze the 1960 map and the map for the years 2071–2100, both available in the bibliography. The comparison with the map presented in Figure 1 (1980–2016) demonstrates previous comments on climate change in the world and reinforces the importance of solutions to increase resilience, such as, in urban areas, RHWS and green roofs.

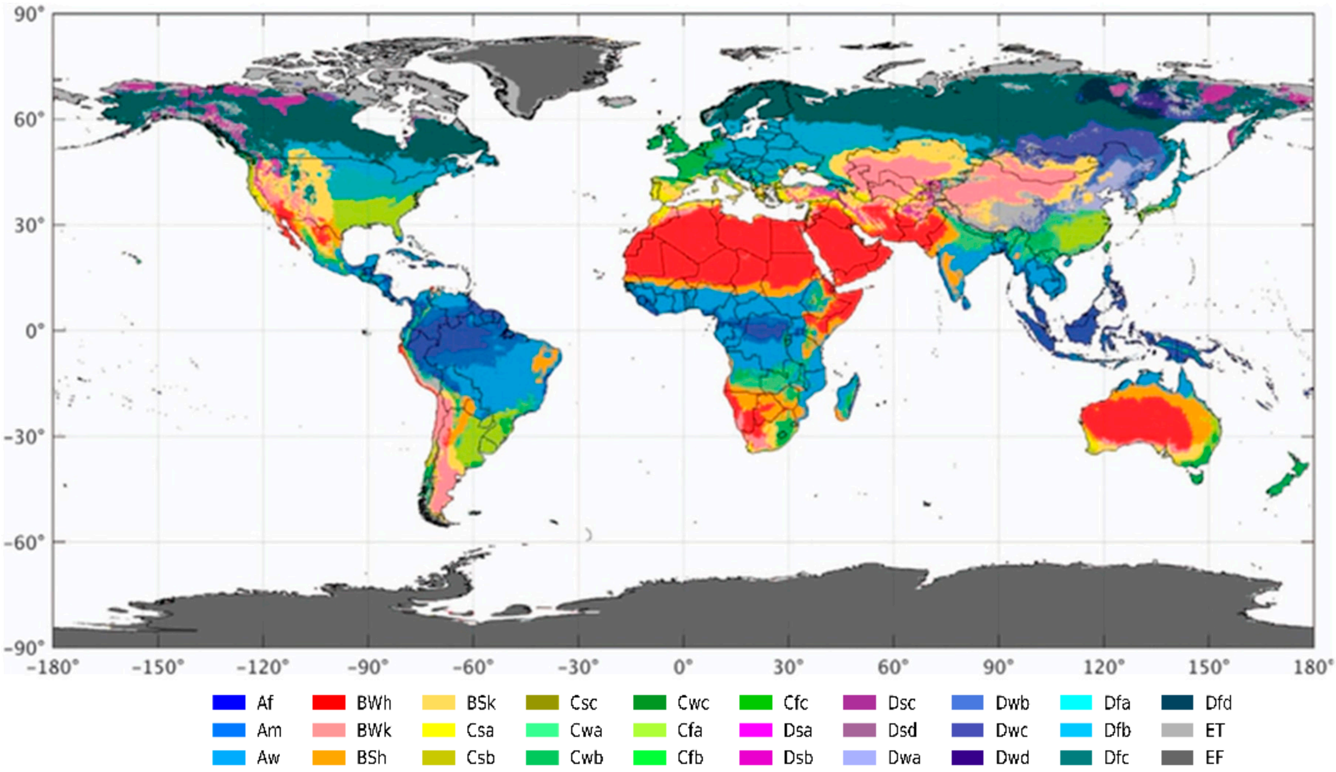

Figure 1. Köppen–Geiger climate classification map (1980–2016) [45].

The goal of this study was to analyze the possibility of using the Köppen climate classification to assess the feasibility of using rainwater harvesting systems in buildings with green roofs, considering case studies in Portugal. Four meteorological stations were studied in the Csb subregion and eight meteorological stations in the Csa subregion in the research, with this study presenting only the results at the two stations in each area to facilitate analysis and conclusions as the results obtained within of each subregion were similar. The conclusions of this study may eventually be generalized to other regions on the planet within the same subgroup.

According to the Köppen classification, the climate of mainland Portugal is divided into two subgroups within the C group: one with a temperate climate with a rainy winter and a dry and hot summer (Csa) and another with a temperate climate with a rainy winter and a dry and slightly hot summer (Csb). The IPMA (Portuguese Institute of the Sea and Atmosphere) presents a map of the Köppen classification for Portugal (Figure 2) [29].

The Csa subgroup (orange in the Figure 2) corresponds to the typical Mediterranean climate, being the most common form of this type of climate. Summers are hot and dry, sometimes similar to summers seen in arid and semi-arid climates, and winters are mild and wet, although very cold winters can occur (even with snowfall). Outside the Mediterranean basin, this Csa climate can be found in southwestern South Africa, southern Australia, and parts of Central Asia and the United States, as shown in Figure 1. The Csb subgroup (green in the Figure 2) is less common in the world and corresponds to hot and dry summers, with rainy winters (usually cold, and sometimes with snowfall). Csb climates are typical of the northwest of the Iberian Peninsula, also occurring in eastern North America (California) and South America (Chile), as well as in southwestern South Africa and southern Australia.

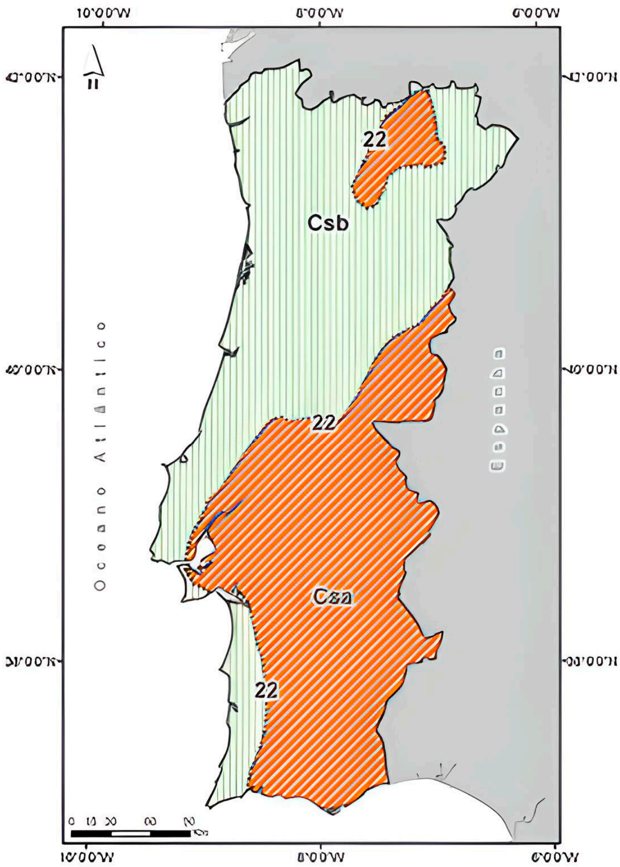

Figure 2. Köppen classification for Portugal (IPMA) [47].

2. Materials and Methods

As previously mentioned, many of the solutions currently considered for cities to adapt to climate change and to achieve greater sustainability in the urban water cycle depend on the climatic characteristics of the regions, with regard to the installation of rainwater collection systems in buildings or the use of these systems in combination with green roofs, enhancing the advantages of both solutions.

For the combination of these two constructive solutions, it is essential to determine the runoff coefficients of green roofs and to assess the volumes of rainwater that can be used in buildings, as well as its temporal distribution. Studies carried out in Oporto, in the north of Portugal, by ANQIP (National Association for the Quality of Building Installations) and by UCP (Portuguese Catholic University), on an extensive green roof, allowed the development of an expression to predict, with an acceptable approximation, the monthly runoff coefficients [48,49].

The pilot green roof adopted followed a typical extensive structure, with usual geotextile membranes, a layer of expanded clay to retain water, and a 10 cm substrate to support the cultivation of plant species, composed of a mixture of expanded clay and organic. This green roof was planted with three different species of native plants common in Portugal and other countries with a Mediterranean climate (*Satureja montana*, *Thymus caespititius* and *Thymus pseudolanuginosus*) [48,49].

Obviously, the expression will only apply to extensive green roofs with the characteristics of the pilot used in the research, but it should be noted that it corresponds to a very common solution in Portugal. The expression was studied for a location within the Csa climate region, but the parameterization of the formula is not conditioned by the characteristics of the region, so it is assumed that the expression can be generalized to other regions, at least to the C group.

The research carried out in Porto allowed the development of an expression to estimate the monthly runoff coefficient [4] as follows:

$$C_M = \mathrm{K}\frac{(P_M + R_M)}{(2T_M - T_{M-1})^{1.2}} \tag{1}$$

where K = 0.016 (°C$^{1.2}$ mm^{-1}), C_M is the runoff coefficient of month M, P_M is the precipitation of month M (mm), R_M is watering in month M (mm), T_M is the mean air temperature during month M (°C), and T_{M-1} is the mean air temperature during month $M-1$ (°C).

According to this expression, the runoff coefficient significantly depends on the temperature in previous periods and on the precipitation, which shows similarities with the well-known Turc formula [50], which is widely used in hydrological studies to determine the flow deficit, considering that this similarity is an indicator of the consistency of the expression [24]. It should be noted that, whenever the application of the formula leads to a C_M value greater than 0.50, it is recommended that this value be adopted as a maximum, considering the indications of the European Standard EN 16941-1 [51] and Technical Specification ETA ANQIP 0701:2007 [52].

Some researchers advocate a theoretical analysis of RHWS operations based on daily data, but this approach is not viable when daily data are not available, as is the case in the selected stations. In any case, other researchers suggest that, given the great variability currently observed in daily meteorological data, analysis based on monthly values is more appropriate, for example, for sizing cisterns in engineering designs [53].

For this research, four meteorological stations were considered, two of them (1—Rio Torto; 2—Viana do Alentejo) located in the Csa subregion and the other two (3—Ponte da Barca; 4—Castelo Burgães Dam) located in the Csb subregion, as shown in Figure 3. For the selected meteorological stations, the monthly precipitation and temperature history is available on the government website SNIRH (National Water Resources Information System) [54].

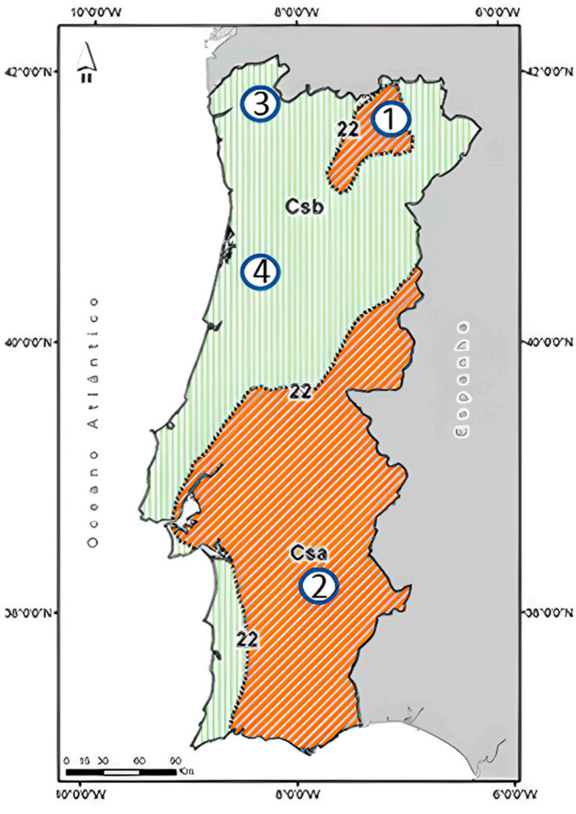

Figure 3. Location of selected weather stations.

The calculation parameters (precipitation and temperatures) corresponding to each of the selected meteorological stations are summarized in Table 1. The values presented correspond to the average of prolonged periods (mainly from the 1930s to the last hydrological year—2021/2022) and are indicated from October onwards, as the hydrological year in Portugal begins on the first day of that month.

Table 1. Monthly averages of temperatures (°C) and precipitation (mm) at selected meteorological stations (1930–2022).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Weather station 1—Rio Torto (Csa)												
Precip.	55.3	61.5	69.5	62.6	60.4	51.5	44.7	42.5	28.7	12.3	10.3	28.6
Temp.	14.9	9.9	7.0	5.4	7.9	10.7	13.0	16.7	20.9	24.0	23.5	20.3
Weather station 2—Viana do Alentejo (Csa)												
Precip.	73.8	82.6	96.9	91.1	76.6	74.7	62.1	46.9	18.8	5.2	5.2	28.4
Temp.	17.4	12.8	10.1	9.4	10.3	12.3	13.7	17.0	20.6	23.4	23.5	21.4
Weather station 3—Ponte da Barca (Csb)												
Precip.	167.1	206.0	238.7	228.1	190.7	178.1	134.8	117.8	59.9	24.8	33.7	86.6
Temp.	15.6	11.9	9.4	8.2	9.3	11.7	13.6	16.2	19.3	21.5	21.7	19.4
Weather station 4—Barragem de Castelo Burgães (Csb)												
Precip.	169.0	206.5	236.3	238.5	196.8	176.5	142.3	129.8	61.6	25.0	31.5	78.7
Temp.	15.7	11.7	9.4	8.6	9.4	11.2	12.6	14.9	18.1	20.3	20.3	18.8

Climate change, with a tendency towards a progressive reduction in precipitation and an increase in temperature in Portugal, could make these average values relatively optimistic for the future, from the perspective of this study. However, it is considered that this effect will not be relevant to the conclusions of this research.

3. Results and Discussion

Based on the expression previously presented and the values in Tables 1–4, it is possible to calculate the monthly runoff coefficients for green roofs (GR) similar to the pilot in the different locations. The results obtained are shown in Table 2.

Table 2. Monthly runoff coefficients for extensive GR in the select locations.

Location	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1—Rio Torto	0.06	0.15	0.20	0.19	0.06	0.04	0.03	0.02	0.01	0.00	0.00	0.02
2—Viana do Alentejo	0.05	0.11	0.15	0.12	0.07	0.05	0.04	0.02	0.01	0.00	0.00	0.01
3—Ponte da Barca	0.14	0.26	0.38	0.35	0.18	0.12	0.08	0.06	0.02	0.01	0.01	0.05
4—Barr. Castelo Burgães	0.13	0.29	0.36	0.32	0.19	0.13	0.10	0.07	0.03	0.01	0.01	0.04

Table 3. Non-drinking water demand in the building [52].

Device	Consumption
Flushing cistern (category "A") in service buildings	4400 L/(person and year)
Wash tap (dominant use for floor washing)	5 L/(m^2 of floor)

The graphical representation of these coefficients is presented in Figure 4. It can be easily observed that, within the same climatic subregion, the coefficients present similar patterns.

Table 4. Simulation of the operation of the RWHS in the location 4 (Csb).

Month	Average Monthly Precipit.	Monthly Water Demand	Monthly Runoff Coefficient	Usable Volume of Monthly Precipit.	Demand/Available Volume Difference	Storage Cistern Volume	Water Volume in the Cistern		Volume Required from Public Network
							Beginning	End	
	(mm)	(m^3)	(-)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)
Oct.	169.00	30.00	0.13	13.18	−16.82	13.00	0.00	0.00	16.82
Nov.	206.50	30.00	0.29	35.93	5.93		0.00	5.93	0.00
Dec.	236.30	30.00	0.36	51.04	21.04		5.93	13.00	0.00
Jan.	238.500	30.00	0.32	45.79	15.70		13.00	13.00	0.00
Feb.	196.80	30.00	0.19	22.44	−7.56		13.00	5.44	0.00
Mar.	176.50	30.00	0.13	13.77	−16.23		5.44	0.00	11.23
Apr.	142.30	30.00	0.10	8.54	−21.46		0.00	0.00	21.46
May	129.80	30.00	0.07	5.45	−24.55		0.00	0.00	24.55
Jun.	61.60	30.00	0.03	1.11	−28.89		0.00	0.00	28.89
Jul.	25.00	15.00	0.01	0.15	−14.85		0.00	0.00	14.85
Aug.	31.50	15.00	0.01	0.19	−14.81		0.00	0.00	14.81
Sep.	78.70	15.00	0.04	1.89	−13.11		0.00	0.00	13.11
Total	1799.00	315.00	-						145.72

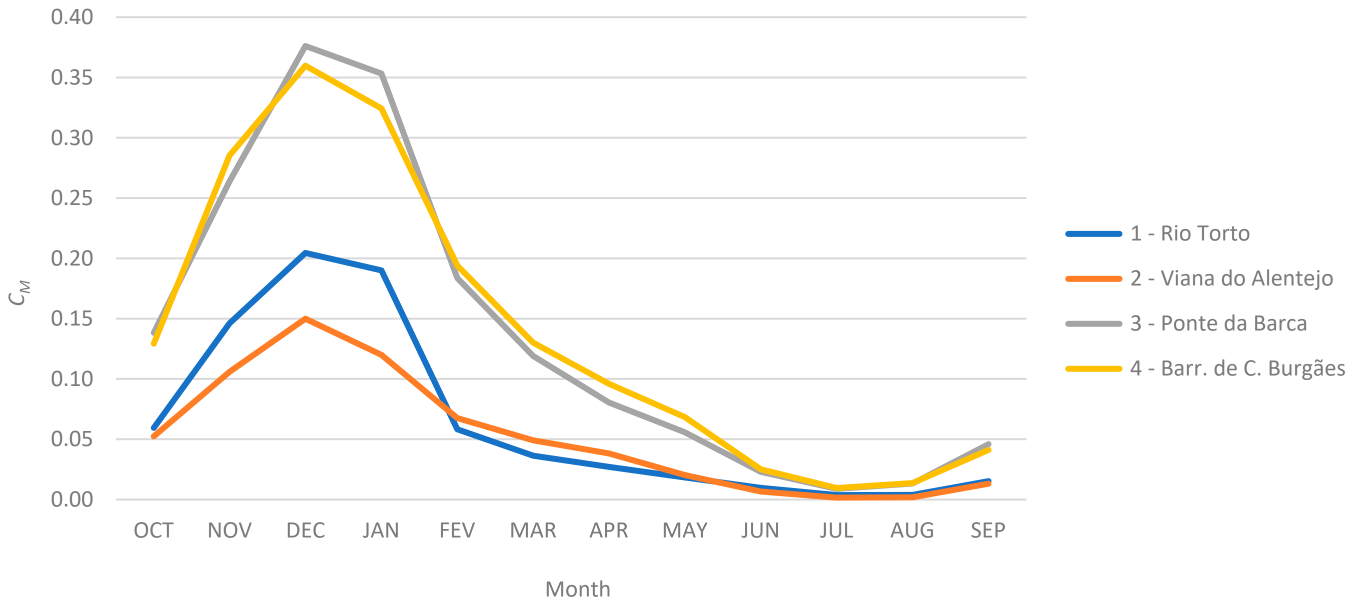

Figure 4. Monthly runoff coefficients in the selected weather stations.

In the case of the Csb climatic subregion, the monthly runoff coefficients reach maximum values between 0.30 and 0.40 in the winter period. In the case of the Csa subregion, runoff coefficients do not exceed 0.20, even in periods of greater precipitation, with almost zero values observed during the summer. These values seem relatively low; however, Equation (1), obtained in previous research, has been experimentally proven and is widely used in Portugal for studies based on average monthly rainfall. The results will probably be different with other extensive green roof solutions or with different vegetation; however, the pilot green roof that was used to obtain Equation (1) corresponds to a common solution in Portugal, as previously mentioned.

At the two meteorological stations located in the Csb subregion, the average value of the runoff coefficient is 0.14, while in the Csa subregion the average values obtained are only 0.05 and 0.06. Although the usable volume of rainwater does not depend only on the runoff coefficients but also on the total volumes of precipitation, values such as those observed in the Csa climate subregion are, from the outset, an indicator of the low viability of an eventual catchment system of rainwater on buildings with green roofs.

To confirm this conclusion, a study is presented below for a building with a green roof (GR) and a rainwater harvesting system (RWHS) located near meteorological station 4 (Csb), as well as a comparison with the results that would be obtained for location 2 (Csa). The total annual precipitation at weather station 4 (Barragem de Castelo Burgães) is 1692.5 mm and at station 2 (Viana do Alentejo) is 662.3 mm.

The considered building is a university building, with 21 sanitary facilities, equipped with toilets with flushing cisterns, and which also has two taps mainly used for general cleaning (floors, etc.). The use of rainwater was considered only for these devices, which do not require drinking water, so showers and sink taps existing in the building were excluded for health and safety reasons. The total area considered for the green roof is 600 m^2.

Regarding the methods and sizing bases, the technical documents applicable in Portugal were observed, namely the Technical Specification ETA ANQIP 0701:2007 [52]. For the sizing of pipe networks, the European Standards EN 806-2:2006 [55], EN 806-3:2006 [56], EN 12056-2:2000 [57], and EN 12056-3:2000 [58] were also observed, as well as other documents applicable to this type of installations, such as the Portuguese regulations.

Considering ETA ANQIP 0701 [52], the monthly volume of rainwater that can be used can be determined in this case by the following equation:

$$V_M = C_M \times P_M \times A \tag{2}$$

where V_M corresponds to rainwater that can be collected in month M (L), C_M is the runoff coefficient of month M (dimensionless), P_M is the precipitation of month M (mm), and A is the catchment area (m^2).

With regard to non-drinking water needs, the values indicated in Annex 2 of ETA ANQIP 0701 [52] were assumed (Table 3). The values indicated the placing of efficient devices to be presupposed, labelled in class "A" or higher in the Portuguese product water efficiency classification system (ANQIP).

It is estimated that there are an average of 80 daily users in the building, considering weekdays and weekends. For the washing of the floors, with a total area of 150 m^2, a monthly frequency was estimated. The annual demand for non-potable water (D) in the building can then be estimated based on the previous assumptions as follows:

$$D = 4400 \times 80 + 5 \times 12 \times 150 = 361{,}000 \text{ L/year} \approx 360 \text{ m}^3\text{/year} \tag{3}$$

This value is equivalent to 30.00 m^3/month. However, in the summer months (July, August, and September) half of this value was considered (15.00 m^3/month), considering that in these months, despite being the months of academic holidays in Portugal, some research activities are maintained.

The volume of the storage tank is usually the most important component of a RWHS project, in economic terms. Technical Specification ETA ANQIP 0701 [52], although it recommends the application of an optimization methodology in large installations, presents some abridged sizing procedures to estimate the volume of cisterns, which is applicable to small systems with traditional coverings. Based on the adaptation of these simplified methods to green roofs, a cistern with a (commercial) volume of 13.0 m3 was adopted for both locations.

Tables 4 and 5 present the simulation of the operation of a RWHS during a hydrological year for the two locations. With regard to safety, it was considered that the storage tank would be empty at the beginning of the annual cycle.

Table 4 demonstrates that, for an average year, the RWHS can fully supply non-potable water needs for 4 months, from November to February. In the remaining months, an additional supply from the public network is necessary to meet the demand, with a total volume of 145.72 m^3. Thus, 169.28 m^3 of rainwater is used in the building (315.00 m^3 − 145.72 m^3 = 169.28 m^3), which means that 54% of the building's non-potable water needs can be supplemented with rainwater (169.28/315.00 = 0.54).

Table 5. Simulation of the operation of the RWHS in location 2 (Csa).

Month	Average Monthly Precipit.	Monthly Water Demand	Monthly Runoff Coefficient	Usable Volume of Monthly Precipit.	Demand/Available Volume Difference	Storage Cistern Volume	Water Volume in the Cistern		Volume Required from Public Network
							Beginning	End	
	(mm)	(m^3)	(-)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)	(m^3)
Oct.	73.80	30.00	0.05	2.21	−27.79	13.00	0.00	0.00	27.79
Nov.	82.60	30.00	0.11	5.45	−24.55		0.00	0.00	24.55
Dec.	96.90	30.00	0.15	8.72	−21.04		0.00	0.00	21.04
Jan.	91.90	30.00	0.12	6.62	−23.38		0.00	0.00	23.38
Feb.	76.60	30.00	0.07	3.22	−26.78		0.00	0.00	26.78
Mar.	74.70	30.00	0.05	2.24	−27.76		0.00	0.00	27.76
Apr.	62.10	30.00	0.04	1.49	−28.51		0.00	0.00	28.51
May	46.90	30.00	0.02	0.56	−29.44		0.00	0.00	29.44
Jun.	18.80	30.00	0.01	0.11	−29.98		0.00	0.00	29.98
Jul.	5.20	15.00	0.00	0.00	−15.00		0.00	0.00	15.00
Aug.	5.20	15.00	0.00	0.00	−15.00		0.00	0.00	15.00
Sep.	28.40	15.00	0.01	0.17	−14.83		0.00	0.00	14.83
Total	662.3	315.00	-						284.06

In the case of the building located in the area of meteorological station 2, Table 5 shows that, for the average precipitation values, the cistern never fills up and that the need for non-drinking water is not completely met by the RWHS in any given month of the year. Only 30.94 m^3 of rainwater is used in the building (315.00 m^3 − 284.06 m^3 = 30.94 m^3), which means that only 10% of the building's non-potable water needs can be supplemented with rainwater (30.94/315.00 = 0.10).

The RWHS cost estimate, in both cases, is EUR 9300.00, including the cistern, accessories and pipes, the pumping group, etc. The public water price in the municipality of location 4 is EUR 2.19/m^3 and is EUR 2.23/m^3 in the municipality of location 2.

In economic terms, water savings in an average year at the current price correspond to EUR 370.72/year (169.28 m^3/year × EUR 2.19/m^3) in location 4 and only EUR 69.00/year (30.94 m^3/year × EUR 2.23/m^3) in location 2. On average, the payback period on investments can be estimated to be at 25 years (9300.00/370.72) for location 4 and 135 years (9300.00/69.00) for location 2. Considering the useful life of RWH systems, which can reach a maximum of 50 years [59], it can be concluded that the system at location 2 is not economically viable. In reality, these payback times will be a little longer, considering interest rates, annual energy costs (pumping), and maintenance costs. However, by observing that these factors are not of high value in relative terms, it can be concluded that they do not alter the conclusions.

It should be remembered that there are benefits in these systems that can reduce the return period, although they are difficult to assess, such as the reduction in runoff peaks, with consequences in the damping of urban floods. However, it is expected that climate change may have some negative effects on the profitability of these systems. In the most severe climate scenarios in Portugal (RCP 8.5, which signifies the highest reference scenario, resulting from continued increases in emissions throughout the 21st century), it is predicted that the reduction in precipitation by 2100 could reach 20 to 40% in the territory, essentially affecting the Csa subregion [47]. However, in addition to the uncertainty of these models in the long run, it is expected that the effects on the Csb subregion will not be as severe.

4. Conclusions

Tackling climate change is one of humanity's biggest challenges in the 21st century. Mitigation measures need to be put in place and, at the same time, "resilience" needs to be increased, i.e., the ability to manage damaging events, disruptions, or trends while maintaining essential functions, identities, and structures.

In urban environments, the construction of green roofs combined with rainwater harvesting systems in buildings is a constructive solution that can maximize the known benefits of each of these technologies, in terms of contributions to mitigation and adaptation. Indeed, this combination holds great promise for tackling climate change and for improving the sustainability of cities, essentially increasing resilience in urban areas in the face of intense hydrological events, not forgetting all the other environmental benefits that can be attributed specifically to green roofs.

For these reasons, a growing number of countries are encouraging or even making these solutions mandatory in cities, and this article essentially aims to assist political decision makers, designers, and builders in this regard. However, the viability of this solution essentially depends on local climatic conditions. In Portugal, a Mediterranean country in southern Europe that will be particularly affected by climate change, there are two well-defined temperate subregions according to the Köppen classification (Csa and Csb). Moreover, this present study led to the conclusion that the GR runoff coefficients, which are the fundamental parameter for the design of GR solutions combined with RWHSs, follow similar patterns in each of these subregions. As a result of this study, it can also be stated that the combined solutions outlined in this article are viable in Portugal in the Csb subregion, but not in the Csa subregion, considering the traditional extensive use of green roof solutions in the country.

This finding allows the Köppen climate classification to be used as a preliminary indicator of the viability of these constructive solutions in each specific location in the country, and it can be used as a criterion for the development of further studies incorporating solutions into buildings. For other regions of the planet with the same climatic characteristics (Csa or Csb), the generalization of these conclusions will naturally require calibration studies, based on the average precipitation in these regions and on experimentally determined runoff coefficients, as well as on the local type of green cover (constitution and thickness of layers, type of vegetation, etc.). Lastly, technical/economic feasibility analyses will require information on water prices, local construction costs, etc.

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