Adaptation measures to climate change. Integration of green roofs with rainwater harvesting systems

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Abstract: - Nowadays it is imperative to assess the effects of climate change and develop mitigation and adaptation measures, particularly in urban environments, as cities will comprise 2/3 of the world's population by 2050, according to the UN. The use of rainwater in buildings can be a good solution to reduce flood peaks of stormwater in public areas, which may increase as a result of climate change, but also to increase water efficiency in buildings. Indeed, hydric stress is increasing on a global scale (especially in the Mediterranean basin) and it is imperative to search for measures to face these consequences. On the other hand, the use of green roofs (GR) in buildings can also bring many advantages, since it also cushions peak flows of stormwater in cities and increases the number of green infrastructures as well as all its associated benefits. Thus, it is possible to state that the GR technology combined with rainwater harvesting systems is particularly promising, pointing to the importance of developing studies that help the combined design of these systems, specifically runoff coefficients. The contributions of roofs to environmental sustainability can be further enhanced by the inclusion, for example, of photovoltaic panels, which conduces mitigation of climate change by increasing the production of renewable energy. In Portugal, a project is under development for modular roofs involving these three technologies, seeking to contribute to greater future sustainability in urban environments. The project involves research related to these different technologies and their integration, and in this paper we present the first results obtained in relation to runoff coefficients, in view of the combination of the green roof with a rainwater harvesting system in regions with a Mediterranean climate. The theoretical results show low values and wide variations in the runoff coefficients, with a minimum of 0.04 and maximum of 0.14, in terms of annual averages, which are significantly lower than the values that are usually suggested in the bibliography. Experimental tests to validate these results are in progress.

Key-Words: Rainwater harvesting, green roofs, runoff coefficients, sustainability, urban planning, climate change.

1 Introduction

Increasing attention is being paid to the potential impacts of climate change on urban environments. According to the United Nations, about 54% of the planet's population currently lives in cities, but it is expected that this percentage will rise to 66% in 2050. Projections show that urbanization combined with the overall growth of the world's population could add another 2.5 billion people to urban populations by 2050, with close to 90% of the increase concentrated in Asia and Africa [1].

More frequent and intense extreme weather events will result in a higher incidence of floods around the planet, leading to a higher risk of floods, while the proportion of land in extreme drought and many semi-arid and arid areas (like the Mediterranean Basin, the western U.S.A., southern Africa and north-eastern Brazil) are exposed and may suffer a decline in water resources [2] [3].

These impacts of climate change on urban environments are starting to be felt and the intensity and frequency of heavy rainfall events and heat waves are expected to increase in the next decades in some regions of the planet [4] [5]. It will be the case of the Mediterranean basin where, together with an increased risk of flooding, the risk of hydric stress or even water scarcity will also increase significantly, and some countries may experience very serious problems in a large part of their territory in the short to medium term [6] [7].

In urban environments, the use of green roofs (GR) on top of buildings may counteract some of these effects, since they cushion the stormwater peak flow and increase the number of green infrastructures that can contribute to the mitigation of the effects of climate change [8]. In addition to the reduction of flood risks in urban areas, green roofs have other environmental benefits, such as the increase of thermal comfort in buildings, with inherent energy savings, the improvement of rainwater runoff quality, the mitigation of urban heat islands, and the provision of wildlife habitats in urban environments [9] [10].

Likewise, rainwater harvesting systems in buildings are particularly suited to address the many impacts of climate change because, in addition to also reducing flood peaks in urban areas, they promote additional water storage in buildings, thus contributing to a mitigation in problems resulting from water scarcity [11] [12].

In most developed cities, roofs account for approximately 40-50% of the urban surface area [13]. So, the construction of GR combined with rainwater harvesting systems (RHS) in buildings can boost the advantages of each of these technologies [14] [15], whereby their combination should be considered a very promising solution to face climate change and increase sustainability in cities [16] [17]. Thus, the development of research that supports the integrated design of these systems, specifically with regard to the determination of runoff coefficients, is becoming increasingly important [18].

The contributions of roofs to environmental sustainability can be further enhanced by the inclusion, for example, of photovoltaic panels, which conduces to a mitigation of climate change by increasing the production of renewable energy. In Portugal, a project is under development for modular roofs involving these three technologies, seeking to contribute to a greater sustainability in the future in urban environments. The project involves research related to these different technologies and their integration, and in this paper the first results obtained in relation to runoff coefficients, in view of the combination of the green roof with a rainwater harvesting system in regions with a Mediterranean climate, are presented.

This ongoing research takes into account not only the traditional systems, but also new solutions for GR that are beginning to be proposed, such as green roofs with expanded cork agglomerate (ICB) [19] or roofs based on modular elements. These solutions are also expected to be light enough to extend their applicability to retrofitting existing buildings with structural limitations [20].

In view of the integration of GR with RHS, previous studies have been developed on a conventional extensive GR system in Oporto city (Portugal). These studies have revealed low values of runoff coefficient but allowed the development of an expression to predict the 'monthly runoff coefficients' for the pilot conventional GR [21]. It should be noted that the concept of extensive GR is applied to green roofs with a maximum depth of about 150 mm.

Monthly runoff coefficients are particularly important for sizing the storage tanks of RHS in Mediterranean climates [22], where there are long dry periods, extending in general throughout the summer period. In other climates, such as in central and northern Europe, where precipitation periods occur in almost all months, RHS sizing is often done on the basis of annual average runoff coefficients.

This study presents the results of the first phase of this ongoing study, with the objective of generalizing and validating the expression previously deduced for the conventional extensive GR, and adjusting it to different locations in the country, with different climatic conditions.

2 Run-off coefficients in conventional extensive green roofs

2.1 Factors that influence the run-off coefficients

When designing a rainwater harvesting system combined with a green roof, several factors should be taken into account, such as the roof runoff coefficient [23] that should be assessed for each particular climate and type of GR.

The runoff coefficient is a dimensionless parameter that depends essentially on roof characteristics. It represents the relationship between the total runoff volume from the roof and the total amount of precipitation in a certain time period [22] and, in impervious roofs, it has a value near one.

Among other studies mentioned in the literature on runoff coefficients in green roofs, can be cited the studies of Schroll et al. [24], which reports less than

28% of rainwater retention on their study during the winter, that was less than half of their retention capacity during the summer, and Spolek [25] which reports a winter stormwater retention of 12% in a green roof (against 42% of retention in summer).

On the other hand, Palla et al. [26], found rainwater retention values between 3-11% on a green roof operating in Genoa-Italy, a Mediterranean city, and Vijayaraghavan et al [27], described 35 % of water retention capacity in one of their green roof pilots located in the Singapore University

In the case of green roofs, the runoff coefficient is dependent mainly on the type of coverage used in the systems, on the type of plants used, and on the characteristics of the substrate, but is also affected by local climatic conditions, especially by temperature and precipitation diagrams. For this reason, in Mediterranean regions, where these diagrams are very different throughout the year, the sizing of RHS storage tanks is usually based on monthly balance sheets, which implies the determination of "monthly runoff coefficients", and not on average annual runoff coefficients, as it is usual in climatic zones of central and northern Europe, for example [28].

The monthly runoff coefficient represents the relation between the total runoff volume from de GR measured during a given month and the total amount of precipitation on the roof in that month, added to the volume of eventual watering done in that period.

2.2 Description of the pilot green roof

The pilot green roof system initially developed for the study of monthly runoff coefficients in a conventional extensive green roof (Figure 1) was located on the top of a building in Oporto, Portugal, at the *Escola Superior de Biotecnologia – Universidade Católica Portuguesa*. This Portuguese city has a Mediterranean climate, although with Atlantic influences.

The extensive pilot system followed the typical extensive GR structure – with geotextile membranes, a water holding capacity layer using expanded clay, and the growing substrate with 10 cm height, composed of a mixture of expanded clay and organic matter [21].

The pilot green roof was established with three different common aromatic plant species: *Satureja montana, Thymus caespititius and Thymus pseudolanuginosus* (Figure 2). These plants are autochthonous in Portugal and in other countries with Mediterranean climates.

Figure 1 – Green roof experimental set up and schematic representation [21]

Figure 2 - Aromatic species used on the pilot extensive green roof (*Thymus pseudolanuginosus, Thymus caespitituis* and *Satureja montana*) [5]

The study was in operation for a period of 12 months (March 2013 - February 2014), through different rainfall conditions [21]. For the calculation of runoff coefficients, the water that drained from the system was manually collected every 24 hours and the volume was measured using a graduated flask. Rainfall, watering and runoff volumes were measured during the year, in order to develop a model to evaluate monthly runoff coefficients of the system [21].

Although wind and atmospheric temperature might influence evapotranspiration and the amount of rainwater retained by the GR system, the goal was only to quantify the amount of runoff rainwater coming out of the system and relate it directly with rainfall and temperatures in prior periods, in order to establish a practical engineering formula, and not to develop an expression that relates runoff with precipitation, evapotranspiration and retention on the roof.

Atmospheric data were provided from a meteorological station from the FEUP (Faculty of Engineering of the University of Oporto), located at a distance of one kilometer from the pilot GR [21].

As stated before, the use of constant runoff coefficient values through all the year for the design of rainwater harvesting systems (or even values for each season), which are proposed in some publications, are revealed manifestly inadequate in Mediterranean climates where there may be extended drought periods in the hot season in opposition to cold and rainy winters [28].

So, in countries with the Mediterranean climate, like Portugal, it is highly recommended that the design of rainwater harvesting systems, in particular the sizing of the storage tank, be made based on monthly average runoff coefficients, as mentioned before [11].

The main goal of the research developed by Monteiro *et al*. (2016) in Oporto was to obtain a practical mathematical expression that allows, with acceptable approximation, determination of average values of the monthly runoff coefficient for a specific extensive GR. Measurements made in the pilot green roof allowed for the development of the following expression for monthly runoff coefficient prediction [21]:

$$C_M = \frac{0.016(P_M - R_M)}{(2T_M - T_{M-1})^{1.2}} \qquad (1)$$

where:

C_M = Runoff coefficient of month *M*
P_M = Precipitation of month *M* (mm)
R_M = Watering of month *M* (mm)
T_M = Mean air temperature of month *M* (ºC)
$T_{M\text{-}1}$ = Mean air temperature of month *M*-1 (ºC)

The obtained expression, which depends significantly on temperature in previous periods and precipitation, has similarities with the well-known Turc formula [29], widely used in hydrological studies to determine flow deficit, that can be considered an indicator of its consistency. Figure 3 shows experimental values obtained vs. the model prediction.

The developed expression (valid for the extensive GR studied and for the specific local climate) revealed a correlation coefficient of 0.81, when compared to experimental values, which can be considered a good approximation, since this type of determination is affected by several other parameters that could not be controlled (e.g. wind). The values obtained for the monthly runoff coefficient are quite reliable, as we can consider that errors in these values are lower than the parameters' variability [21].

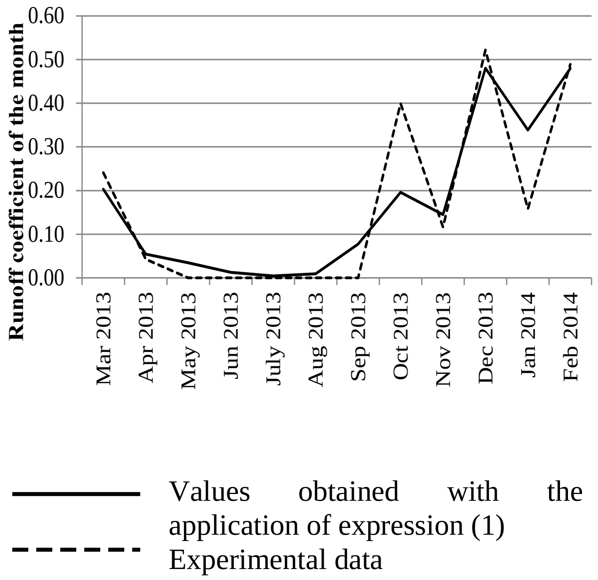

Figure 3 – Monthly runoff coefficient of the pilot GR system.

3 Methods

As previously mentioned, experimental studies carried out for an extensive green roof pilot system in a city in the north of Portugal (Oporto) have allowed for the development of an expression to predict a 'monthly runoff coefficient' for that GR and its specific local climate.

This expression can be written in the general form:

$$C_M = \frac{k_1(P_M - R_M)}{(k_2 T_M - T_{M-1})^{k_3}} \qquad (2)$$

where:

$k_1 = 0.016$
$k_2 = 2.0$
$k_3 = 1.2$

This paper presents the results of the first phase of a current research aiming to generalize and validate this expression in different locations in the country and for green roofs with distinct characteristics, specifically for the GR with modular elements, in development. The experimental tests are in progress, within a research project, with the specific objective of determining the coefficients of the expression (k_1, k_2 and k_3) in these different conditions, admitting the validity of the expression in its general form.

In a first phase, based on the expression and coefficients previously determined for the pilot green roof in a particular location (Oporto) and not considering changes in the characteristics of the GR, theoretical values were determined for several zones of Portugal with different climatic characteristics.

These theoretical results are obtained from the application of expression 1 to 12 weather stations of Portugal where it is possible to get temperature and precipitation values (data available in http://snirh.apambiente.pt). The locations of the different stations considered are marked in Figure 4.

In a second phase (in progress), some particular locations are used for experimental measures, aiming to adjust the coefficients (k_1, k_2 and k_3) and validate the expression for different locations.

It should be noted that northern Portugal has a significant Atlantic influence, where the Mediterranean climate is less dominant. This is the case of stations 1 and 2. Station 3, although located also in the north of Portugal, is situated in the Douro valley, which has a very specific local climate.

The values obtained for the monthly runoff coefficient range from a minimum of zero (in the summer in most meteorological stations) and a maximum of 0.44 in one of the stations in rainy northern Portugal.

4 Results

The theoretical results, obtained by the application of expression 1 in different zones of Portugal, are represented in Figure 5 and Table 1. These results were obtained on the basis of the mean values calculated from the records available for the hydrological year 1980/1981, up until 2015/2016.

Figure 4 – Portuguese weather stations with information available

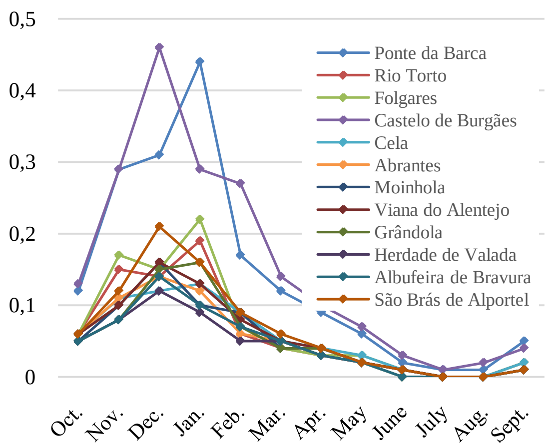

Figure 5 – Monthly runoff coefficient for the different stations (2015-2016).

As an example, for the Abrantes weather station the average values available for the month of December are:

$P_{Dez.}$ = 91 mm
R_{Dez} = 0 mm
$T_{Dez.}$ = 10 ºC
$T_{Nov.}$ = 13 ºC

from which we obtain a monthly runoff coefficient of 0.14 and an estimation for the average usable volume of water in this month (per square meter of roof) of:

$$V_{Dez.} = 0.14 \times 91 = 12.7 \text{ mm} = 12.7 \text{ L/m}^2$$

In terms of annual averages, the values obtained were a minimum of 0.04 and a maximum of 0.14. It should be noted that these values are clearly lower than the average annual runoff coefficients proposed in the literature for green roofs in central/northern European countries, which sometimes are close to 0.3 for intensive green roofs and 0.5 for extensive green roofs.

A detailed study carried out in Germany in a specific extensive green roof [28] revealed runoff coefficients varying between 0.23 and 0.38. During summer values of 0.16 to 0.31 and in winter values of 0.40 to 0.60 were observed for the runoff coefficient, which, in any case, reveals higher values than those obtained in Portugal.

Table 1: Results of the application of the expression 1 to different stations of Portugal (monthly runoff coefficients)

STATION	HYDROLOGICAL YEAR 2015/2016											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
Ponte da Barca	0,12	0,29	0,31	0,44	0,17	0,12	0,09	0,06	0,02	0,01	0,01	0,05
Rio Torto	0,06	0,15	0,14	0,19	0,06	0,04	0,03	0,02	0,01	0,00	0,00	0,02
Folgares	0,06	0,17	0,15	0,22	0,07	0,04	0,03	0,03	0,01	0,00	0,00	0,02
Castelo de Burgães	0,13	0,29	0,46	0,29	0,27	0,14	0,10	0,07	0,03	0,01	0,02	0,04
Cela	0,06	0,11	0,12	0,13	0,09	0,05	0,04	0,03	0,01	0,00	0,00	0,02
Abrantes	0,06	0,11	0,14	0,12	0,06	0,05	0,03	0,02	0,01	0,00	0,00	0,01
Moinhola	0,05	0,10	0,16	0,10	0,09	0,04	0,04	0,02	0,01	0,00	0,00	0,01
Viana do Alentejo	0,06	0,10	0,16	0,13	0,08	0,05	0,04	0,02	0,01	0,00	0,00	0,01
Grândola	0,05	0,08	0,15	0,16	0,07	0,04	0,04	0,02	0,00	0,00	0,00	0,01
Herdade de Valada	0,05	0,08	0,12	0,09	0,05	0,05	0,03	0,02	0,01	0,00	0,00	0,01
Albufeira de Bravura	0,05	0,08	0,14	0,10	0,07	0,05	0,03	0,02	0,00	0,00	0,00	0,01
São Brás de Alportel	0,06	0,12	0,21	0,16	0,09	0,06	0,04	0,02	0,01	0,00	0,00	0,01

Interestingly, in the two weather stations with Atlantic climatic influence the observed results are significantly different from the others, and it is notorious that the results follow similar patterns in the weather stations with dominant Mediterranean climates.

The values obtained, while still lacking the validation that will be obtained with the experimental work in progress, already indicate that the use of RHS combined with GR in Mediterranean countries may involve the construction of large tanks to store water from the rainy season for use in the dry season, or demand a supply system from another source (a public network, for example) to ensure supplies in the dry season. This means that the cost of these integrated systems will be higher in Mediterranean climates than similar systems in typical climates of other parts of central and northern Europe, although its technical and economic viability can also be interesting given the growing scarcity of the resource and the need for adaptation and increased resilience to climate change effects.

This project also includes, at a later stage, an analysis of the physical-chemical characteristics of the runoff and its suitability for possible uses in the buildings of the recovered rainwater.

For this purpose, water samples were periodically collected in the pilot GR for analysis (pH, conductivity, turbidity, chemical oxygen demand, phosphorous (PO_4^{3-}), and nitrogen, in the form of NH_4^+ and NO_3^-) [12]. This chemical analyses were based on standard methods.

The data obtained for a one year period (March 2013 – March 2014) comprised average values for turbidity of 7.42 NTU, pH of 7.53, conductivity of 14 µS cm^{-1}, NH_4^+ (mg N/L) of 0.11, NO_3^- (mg N/L) of 1.22 and PO_4^{3-} (mg P/L) of 1.41. Chemical oxygen demand was in general under the detection limit.

Water quality parameters are summarized in Table 2

Table 2: Characterization of the green roof runoff for a one year period

Parameter	Average ± σ
Turbidity (NTU)	7.42 ± 4.58
pH	7.53 ± 0.25
Conductivity (µS/cm)	146 ± 54
NH_4^+ (mg N/L)	0.11 ± 0.14
NO_3^- (mg N/L)	1.22 ± 0.94
PO_4^{3-} (mg P/L)	1.41 ± 0.18

In Portugal there exists a technical specification for rainwater harvesting in buildings (ETA 0701) that was published by ANQIP, a civil society association that promotes quality and efficiency in buildings installations of water supply and drainage [22]. As this specification has been formulated by a non-governmental body, compliance with it is voluntary.

The specification ETA 0701 has 6 chapters (Introduction, Definitions, Legal and regulatory references, General aspects and certification, Technical Provisions and Maintenance), and considers the following possible uses:

- Toilet storage tank flushing
- Washing clothes
- Washing floors, cars and so on.
- Watering gardens, lawns, parks etc.
- Industrial uses (cooling towers, firefighting systems, HVAC, etc.)

It is felt, moreover, that the use of untreated rainwater for toilet flushing should only be acceptable if the water quality is at least up to that of bathing water pursuant to the applicable European directives (Directive 2006/7/CE of 15 February 2006). It may be disinfected with chlorine or a similar process, if necessary.
Clothes should only be washed with rainwater that has had no specific treatment if the washing water temperature reaches at least 55ºC. A micro filter with a minimum mesh of 100 µm should be fitted if the water is to be used for this purpose. If the pH of the rainwater is lower than 6.5 then pH correction may be necessary or appropriate, depending on the materials used in the installation.
Looking at the first analytical results (Table 2), it can be noted that, given the intended uses, the parameter that can raise greater concern is the turbidity which is caused by the presence of suspended materials, which in less dynamic conditions can sediment quickly. This will imply a more careful design of the storage tank, where these sedimentation processes generally occur.
ANQIP is currently developing a new technical specification (ETA 0703) for specific situations of rainwater harvesting from GR runoffs, where particular attention is given to the design of the storage tank inlet and outlet devices, aiming at reduce turbulence and promote sedimentation. This technical specification will also include sizing criteria for the drains and other constructive aspects.

5 Conclusions

The integration of green roofs with rainwater harvesting systems seems a promising solution that can contribute greatly to a very appropriate response to the impacts of climate change in urban areas. These solutions should be widely generalized, preferably with a mandatory character in some regions.
However, the design of these combined solutions depends heavily on the characteristics of the green roof and the particularities of local or regional climates. For this reason, research in this field is needed at present. Experimental studies carried out for a conventional extensive green roof pilot system, in Oporto city, Portugal, have allowed for the development of an expression to predict a 'monthly runoff coefficient' of the green roofs [21], which is the parameter usually used for the sizing of storage tanks in Mediterranean countries.
As part of an ongoing research project in Portugal aiming at the creation of modular green roofs integrating rainwater harvesting and photovoltaic panels, the adaptation of this expression for different places of the country, with distinct climatic characteristics, was studied.
The theoretical results, not considering the specific characteristics of green roofs, show wide variations in monthly runoff coefficients, with a minimum of zero and maximum of 0.44. The results also show that these coefficients depend significantly on the climatic characteristics of the site, indicating very relevant differences between the areas of Portuguese territory with dominant influence of the Atlantic climate and the predominantly Mediterranean climate zones. Experimental tests to validate the expression in different locations are currently in progress.
This project also includes, at a later stage, an analysis of the physical-chemical characteristics of the runoff and its suitability for possible uses in the buildings of the recovered rainwater. It is expected that the conclusions of this analysis will be included in a technical specification to be published by ANQIP, the Portuguese association that promotes water efficiency in buildings.

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