Contributions to the design of rainwater harvesting systems in buildings with green roofs in a Mediterranean climate
Cristina M. Monteiro, Cristina S. C. Calheiros, Carla Pimentel-Rodrigues, Armando Silva-Afonso and Paula M. L. Castro

ABSTRACT
Green roofs (GRs) are becoming a trend in urban areas, favouring thermal performance of buildings, promoting removal of atmospheric pollutants, and acting as possible water collection spots. Rainwater harvesting systems in buildings can also contribute to the management of stormwater runoff reducing flood peaks. These technologies should be enhanced in Mediterranean countries where water scarcity is increasing and the occurrence of extreme events is becoming very significant, as a result of climate change. An extensive pilot GR with three aromatic plant species, Satureja montana, Thymus caespititius and Thymus pseudolanuginosus, designed to study several parameters affecting rainwater runoff, has been in operation for 12 months. Physico-chemical analyses of roof water runoff (turbidity, pH, conductivity, NH₄⁺, NO₃⁻/CO₃²⁻, PO₄³⁻/CO₃²⁻, chemical oxygen demand) have shown that water was of sufficient quality for non-potable uses in buildings, such as toilet flushing. An innovative approach allowed for the development of an expression to predict a ‘monthly runoff coefficient’ of the GR system. This parameter is essential when planning and designing GRs combined with rainwater harvesting systems in a Mediterranean climate. This study is a contribution to improving the basis for the design of rainwater harvesting systems in buildings with extensive GRs under a Mediterranean climate.

Key words | runoff coefficient, Satureja montana, stormwater management, Thymus caespititius, Thymus pseudolanuginosus, water runoff

INTRODUCTION
Increasing attention is being paid to the negative impacts of expanding urban infrastructures and replacement of vegetated landscapes by impervious surfaces in city centres. The impacts of climate change on urban environments are starting to be felt and the intensity and frequency of heavy rainfall events are expected to increase in the next decades (Chalmers 2014). The design of buildings and public spaces that are capable of dealing with the effects of climate change is crucial. The use of green roofs (GRs) on top of buildings may counteract some of these effects since it reduces the flow of stormwater and increases the number of green infrastructures contributing to the mitigation of climate change.

The implementation of GRs can have many environmental and economic benefits, such as mitigation of the urban heat island effect, improving air quality in urban areas, adding aesthetic value to urban architecture, enhancing biodiversity and increasing the life span of the building materials (Berndtsson 2010; Maclvor et al. 2013). On the other hand, the construction of GRs combined with rainwater harvesting systems appears as a fundamental measure to reduce peak flows in the drainage of stormwater (Kasmin et al. 2010; Stovin 2010). Improving stormwater management systems for rainwater harvesting in buildings is particularly appropriate to address the many impacts of climate change because, besides reducing the flood peaks in urban areas, it promotes additional water storage in buildings (Silva-Afonso & Pimentel-Rodrigues 2011).

The combination of a GR with a rainwater harvesting system is a particularly promising tool in the Mediterranean...
basin. When designing a GR structure to mitigate urban runoff, we should take into account several factors such as rainfall intensity and substrate hydraulic properties as well as the roof runoff coefficient (Lee et al. 2013), which should be assessed for this particular climate.

The runoff coefficient is a dimensionless parameter that depends on the characteristics of the roof surface. It is calculated based on the total runoff volume and the total amount of precipitation in a certain time period (ANQIP 2015). Even if the roof water runoff coefficient can be considered valid within similar climatic zones, it is dependent on the type of coverage used in the systems, on the type of plants used and on the characteristics of the substrate, and there is still a large potential for research in this area.

Among the layers that constitute GR systems, the substrate layer is one of the most important. Additionally, selection of adequate vegetation species for GR coverage (adapted to local weather conditions) is of great importance. Aromatic plant species are native to and typical of the Mediterranean zones. Vegetation to be used in the severe environment that GRs can face, as a result of high exposure to solar radiation, wind, wide temperature fluctuation and limited water availability, should be drought tolerant, have low maintenance and present resilience to different environmental conditions; many aromatic species present such characteristics. Sedum species are traditionally used in GR structures; however, they are not effective in reducing water runoff from GRs due to their low height and small shoot and root biomass (Nagase & Dunnet 2012). Aromatic species due to their larger shoot and root biomass may promote water runoff reduction. For that reason, three aromatic plant species have been selected for our system investigation.

The goal of the present research study was to set up an extensive GR structure in a Mediterranean climate, with a selected substrate and different aromatic plant species, in the specific perspective of its combination with a rainwater harvesting system in the building. Water runoff of the system has been evaluated and a model that allows determination of monthly water runoff coefficients required to design adequate harvesting water systems has been developed. Growth of vegetation and water quality runoff were also assessed.

MATERIAL AND METHODS

Green roof pilot system

The GR pilot system was located on the top of a building at Escola Superior de Biotecnologia–Universidade Católica Portuguesa, Porto, Portugal, at the level of a fifth floor. The pilot system of 0.5 m² (Figure 1) followed the extensive GR structure – with two geotextile membranes (to protect the roof structure and filter the vegetation substrate to the drainage layer), a water holding capacity layer using expanded clay Leca® L (to retain water), and the growing substrate, composed of a mixture of expanded clay Leca® Hydro and organic matter (garden soil to provide the adequate support and nutrients for plant growth). Substrate depth has been settled at 10 cm height, a reasonable average depth for extensive GRs, taking into account the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftshaue) guidelines (FLL 2008). Expanded clay has been selected, due to its low weight and water holding capacity.

The GR pilot system was established with three different aromatic plant species – Satureja montana, Thymus pseudo-lanuginosus and Thymus caespititius. All the plants were propagated in organic farming mode and then transplanted to our system and planted by hand. The system was inspected for vegetation growth and weed removal once a month. The study was in operation for a period of 12 months – March 2013 to February 2014 – through different rainfall conditions in a Mediterranean climate.

Water runoff sampling and analysis

Samples of the water runoff from the system (composed of the total accumulated water runoff every 24 h) were...
collected for analysis of water quality, selected from aleatory multiple rainfall events over a 1 year period. The following parameters were determined, based on Standard Methods (APHA 1998): pH, conductivity, turbidity and chemical oxygen demand (COD). The concentration of phosphorus, ammonium and nitrate (PO₄³⁻, NH₄⁺ and NO₃⁻) was determined with photometric test kits (Spectroquant®). The analyses were done immediately after sample collection.

Runoff coefficient

The rainwater runoff of the GR system was assessed, after 20 days of plantation for root establishment. For the calculation of runoff coefficient, the effluent water that drained directly from the system was manually collected in a jerrycan every 24 hours and the volume was measured using a graduated flask. Rainfall-runoff effluent volume was measured for several rainfall events from March 2013 to February 2014, a total of 51 aleatory rain events, in order to develop a model to evaluate monthly runoff coefficients of the system. Although atmospheric temperature might influence evapotranspiration and the amount of rainwater retained by the GR, our goal was to quantify the amount of rainwater that runs off the system and relate it directly with rainfall and temperatures in prior periods and not to establish relationships with evapotranspiration and retention on the roof. Atmospheric data were provided from a meteorological station from FEUP (Faculdade de Engenharia da Universidade do Porto), located 1 km distant.

Data analysis

The monthly runoff coefficient was estimated by non-linear regression analysis with the Solver package of Microsoft Excel 2010 (Microsoft® Corporation, Redmond, WA, USA) using the generalized reduced gradient non-linear algorithm. The standard deviation of the experimental error and the coefficient of determination ($R^2$) were calculated as statistical indicators of the quality of the regression.

RESULTS AND DISCUSSION

The possibility of a pilot GR combined with a rainwater harvesting system was considered, to develop a model to calculate and predict the monthly runoff coefficient, an essential parameter when designing a GR with the purpose of rainwater runoff delay and storage for other uses.

Aromatic species selection for the present study was based on plant tolerance to the climate of the region as they might be more adapted to climate changes. Tolerance to extreme ambient conditions (temperature and humidity), low maintenance requirement, resistance to drought conditions and consequently low water needs are key characteristics for this type of technology.

Growth and development of vegetation was followed, revealing a good adaptation to the tested substrate for all the aromatic plant species used (data not shown). Growth rate at the end of the experiment has been calculated relative to the initial plant size. The highest growth rate of 155% has been achieved by S. montana, followed by T. caespititius and T. pseudolanuginosus with 80% and 59% growth rates, respectively. The use of different plant species is important in this type of construction in order to select vegetation combinations that promote and enhance water retention to attenuate peak flow.

Around the world, there are several types of GR (e.g. on top of restaurants and hospitals) planted with aromatic species. However, to our knowledge, aromatic plants selected for this study have not yet been applied in extensive GR systems designed to test water runoff reduction in combination with rainwater harvesting systems. The aromatic plants used in the present experiments have shown to be a good option for GR vegetation, since they have resisted the operating conditions, with the advantage of usage in other economical areas (food and cosmetic industries).

GR water runoff characterization for the experimental period comprised average values for turbidity of $9.81 \pm 3.09$ NTU ($n = 4$), pH of $7.55 \pm 0.26$ ($n = 24$), conductivity of $147 \pm 55 \mu$S cm⁻¹ ($n = 24$), NH₄⁺ (mg N/L) of $0.11 \pm 0.14$ ($n = 4$), NO₃⁻ (mg N/L) of $1.35 \pm 1.03$ ($n = 4$) and PO₄³⁻ (mg P/L) of $1.46 \pm 0.17$ ($n = 4$). COD was in general under the detection limit ($n = 24$). It should be noted that some samples included first flush water runoff, which is known to largely affect water quality.

The results obtained indicate that the water that flows from our system might be re-used for non-potable purposes, such as irrigation, flushing toilets or pavement cleaning, with regard to its physico-chemical parameters, using GR water runoff coupled with an adequate rainwater harvesting system, with first flush discharge (ANQIP 2015). Microbiological water quality was not assessed. However, investigations carried out in Germany revealed that rainwater harvested for use directly in washing machines without any treatment is safe (Bertolo 2006). Furthermore, if rainwater harvested is to be used outdoors, such as for garden irrigation, water treatment might also be
unnecessary. Newton et al. (2007) referred to one example of a GR where water runoff is harvested for non-potable uses like toilet flushing – Norfolk Community Primary School in Sheffield, UK.

Nowadays, water re-use is of extreme importance, since we are facing adverse dry events and there is a high use of potable water for non-potable situations. In Portugal, and in Europe, there is no legislation or technical specifications regulating the runoff quality of water that flows from GR structures to be later used in other purposes.

The only reference parameter is pH, and our results are in accordance with reference values between 6.5 and 8.5 (ANQIP 2015). Teemusk & Mander (2011) reported that the quality of water runoff in several GRs in Estonia was affected mainly by the materials that constituted the substrate layer. Water quality was comparable to the present study, except for PO43−, where we obtained higher values (1.46 ± 0.16 mg P/L against 0.64 mg P/L maximum achieved).

Rainwater runoff delay into the public sewage systems is one of the major benefits of using GRs that could be enhanced with retention systems. In general, the design of harvesting tanks for rainwater harvesting systems in buildings is based on one average annual runoff coefficient of the roof. Constant runoff coefficient values through the year for GR systems (or even values for each season) are revealed to be manifestly inadequate in Mediterranean climates where there may be extended drought periods in the hot season in opposition to rainy winters (Uhl & Schiedt 2008) when compared with countries in north or middle Europe. On the other hand, and even in a Mediterranean country like Portugal, differences in exposure conditions can be felt between cities, since the climate characteristics can differ in just a few kilometres distance.

Figure 2 illustrates the atmospheric conditions (precipitation and air temperature) variation through the year of our experiments, compared to the average of the year. This variability through the seasons supports the significance of studies concerning runoff coefficients and development of mathematical expressions for determination of average monthly runoff coefficients.

In the Mediterranean climate it is highly recommended that the design of the storage tank for rainwater harvesting, should be made based on monthly average runoff coefficients (Silva-Afonso & Pimentel-Rodrigues 2014). Therefore the present study focuses on obtaining a practical mathematical expression, user-friendly, that allows, with acceptable approximation, determination of average values of the monthly runoff coefficient for a particular GR:

\[
C_M = \frac{[0.016(P_M + R_M)]}{(2T_M - T_{M-1})^{1.2}}
\]

where \(C_M\) = runoff coefficient of the month M; \(P_M\) = precipitation of the month M (mm); \(R_M\) = irrigation of the month M (mm); \(T_M\) = mean air temperature of the month M (°C); \(T_{M-1}\) = mean air temperature of the month M−1 (°C).

The obtained expression has similarities with the well-known Turc formula (Chow 1964), widespread in hydrological studies to determine flow deficit, which 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) revealed a coefficient of determination of 0.81 when compared to experimental values, which can be considered an excellent approximation, since this type of determination is affected by several other parameters that could not be controlled (e.g. wind). The obtained value for runoff coefficient is quite reliable as we can consider that the error of this value is lower than the parameters’ variability.

In the literature concerning water runoff coefficients of GR systems, there are no other expressions with monthly
runoff coefficients; only models giving a constant value during the whole year can be found (Vesuviano et al. 2014; Nophadrain BV 2015). Therefore, the expression developed and the monthly runoff coefficient obtained in the present study are of extreme significance.

The percentage of water runoff through the system, based on the amount of total precipitation that could be later stored and used for non-potable purposes, is presented in Table 1.

Among the literature published on this topic, only references to the amount of water retention have been found (Spolek 2008, Palla et al. 2008; Vijayaraghavan et al. 2012). Water runoff from GR systems for storage and later reuse is not studied. It should also be noted that water retention capacity depends on local weather conditions and on substrate water saturation due to prior rainfall events and physical configuration (Speak et al. 2013; Stovin et al. 2013).

The amount of water that the substrate used in our GR structure could retain has been calculated to be ca. 30%, (i.e. 1 m³ retains 301 L) which is in accordance to the literature published. Spolek (2008) reported winter stormwater retention of 12% in a GR (against 42% of retention in summer). On the other hand, Palla et al. (2008) found rainwater retention values between 3 and 11% on a GR operating in Genoa, Italy, a Mediterranean city, and Vijayaraghavan et al. (2012) described 35% of water retention capacity in one of their GR pilots located in Singapore University.

### CONCLUSIONS

Mediterranean countries are among those with high risk of water stress. It is crucial to develop water efficiency measures, like rainwater harvesting in buildings.

In the current research study an extensive pilot GR has been developed in order to assess its capacity for rainwater runoff delay, when exposed to Mediterranean climate conditions. The developed model for monthly runoff coefficient determination has revealed a good correlation factor with data of water released from our system, and so it could be used to predict the amount of water runoff that could be stored for later reuse. Additionally, monthly runoff coefficient determination is significant as it allows the prediction of the runoff flow of the system in the Mediterranean climate, where rain events vary throughout seasons over the year.

It should be highlighted that runoff coefficient determination also strongly depends on the GR typology adopted. So, the present results should naturally be improved with extended registration periods and should be developed with studies on GRs with other characteristics. However the present study allowed development of an adequate approach to calculate the runoff coefficients, showing that there are significant variations throughout the year, that advise against the use of annual average coefficients in sizing the tanks and other components of rainwater harvesting systems in a Mediterranean climate.

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### Table 1 | Rainwater runoff for harvesting

<table>
<thead>
<tr>
<th>Total precipitation (mm)</th>
<th>Water runoff (%)</th>
<th>Average air temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2013</td>
<td>352.4</td>
<td>12</td>
</tr>
<tr>
<td>April 2013</td>
<td>91.8</td>
<td>2</td>
</tr>
<tr>
<td>May 2013</td>
<td>60.2</td>
<td>0</td>
</tr>
<tr>
<td>June 2013</td>
<td>40.2</td>
<td>0</td>
</tr>
<tr>
<td>July 2013</td>
<td>11.2</td>
<td>0</td>
</tr>
<tr>
<td>August 2013</td>
<td>25.0</td>
<td>0</td>
</tr>
<tr>
<td>September 2013</td>
<td>185.0</td>
<td>0</td>
</tr>
<tr>
<td>October 2013</td>
<td>286.0</td>
<td>15</td>
</tr>
<tr>
<td>November 2013</td>
<td>94.4</td>
<td>4</td>
</tr>
<tr>
<td>December 2013</td>
<td>389.7</td>
<td>20</td>
</tr>
<tr>
<td>January 2014</td>
<td>399.4</td>
<td>6</td>
</tr>
<tr>
<td>February 2014</td>
<td>455.2</td>
<td>19</td>
</tr>
<tr>
<td>Annual average 2013 IPMA</td>
<td>939.0</td>
<td>15</td>
</tr>
<tr>
<td>Annual average 2014 IPMA</td>
<td>1098.2</td>
<td>15</td>
</tr>
</tbody>
</table>

IPMA, Portuguese Institute of Meteorology.
REFERENCES


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