The contribution of a spring water source to the water needs of the botanical garden of the University of Coimbra

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ABSTRACT

In general, cities have developed and expanded in places where natural and environmental conditions were the most favourable, and they can only continue to prosper by conserving the natural resources that are the drivers of their wealth and quality of life. Four out of five European citizens live in urban areas and the quality of life is greatly influenced by the urban environment. Here, gardens, parks and green open spaces improve air quality and reduce the impact of stormwater events by reducing the value of the runoff coefficient; they offer lower temperatures in hot urban islands and represent habitats for biodiversity. Gardens in many cities, such as our case study of Coimbra, were initially built for decorative, architectural, and leisure purposes, or with specific academic goals in mind, but their size or urban relevance often made them important factors in city planning and resources’ sustainability, as well as for the wellbeing of their citizens. Sustainable water management in urban areas involves promoting rational water use, and also the identification of strategic reserves to deal with droughts when they occur. By improving the management of the urban water cycle as a whole a more efficient use of resources can be achieved, providing not only economic benefits but also improving social and environmental outcomes. Because water is a limited and scarce resource it must be used in gardens in an efficient and sustainable way. For this reason grasses, trees, shrubs and flower beds must be provided only with enough water to satisfy their needs. Using the Landscape Coefficient Formula, the amount of water needed for irrigation can be expressed as a percentage of reference evapotranspiration (ET₀). The value of evapotranspiration should be adjusted to best meet the water demands of a given assortment of plant species. In this paper we present a study performed at the Botanical Garden of the University of Coimbra (BGUC). Monthly and annual levels of precipitation were evaluated along with the air temperature and evapotranspiration to determine the climatological water balance through water shortages and surpluses. The results were compared with the levels of water consumption (from the water supply and spring water collector) and the efficiency of irrigation was assessed, adjusted for plant type, enabling the identification of procedures and opportunities to maximize the efficient use and sustainable management of water.

Key words | Coimbra Botanical Garden, sustainable water management, urban environment, urban parks

INTRODUCTION

Cities developed and expanded in places where natural and environmental conditions were favourable, and they can only continue to thrive as long as they safeguard the natural resources that are the drivers of wealth and quality of life for their citizens. Four out of five European citizens (ECE 2006) live in urban areas and their well-being and quality of life are directly influenced by the state of the urban environment; a good urban environment is a prerequisite for good quality of life.
Shaped by humans to meet their demands, cities are complex artificial ecosystems and are subject to environmental challenges that have significant implications for human health, quality of life and the city’s economy. It is widely recognized that parks, gardens and green spaces help to improve the ecological sustainability of the city and make it more attractive and healthy (Smaniotto Costa 2008, 2009).

Gardens, parks and green open spaces help to enhance air quality (Allen et al. 2008), to reduce the impact of stormwater events (Girling & Kellett 2002), to reduce temperatures in hot urban island effects (Barradas 2000), and they also offer habitats for biodiversity, which plays a significant role in improving life in urban communities. Botanic gardens of many cities were, like our case study, initially built for decorative, architectural, and leisure – or pharmaceutical and medicinal plant – purposes, but their size or relevance often made them significant factors in the planning and sustainability of cities and the comfort and well-being of their citizens. Urban green spaces are environmental assets of great importance for any city and a critical element of urban quality of life.

Projections for climate change claim that summers are going to be warmer and dryer, with more frequent extremes of temperature. Trees not only lower the ambient temperature in their microclimate through evaporative cooling, they are also effective at retaining storm water and therefore relieving pressure on drainage systems (Gill et al. 2007).

Large parks and/or green open spaces are important to the sustainability of water management in urban areas, providing strategic reserves to deal with drought as well as promoting control and rational water use. The damping effect of floods promotes an increase in the runoff coefficient, reduces the impact of water droplets and the effects of erosion, and increases infiltration and aquifer recharge. These green open spaces should be seen as low impact infrastructures that promote runoff control at source (flood management) and help to maintain or restore natural hydrology.

People living in cities value parks and green areas for their amenities as well as for the presence of nature in urban environments, but parks and green areas offer several other benefits. Climate changes and urban expansion are challenges that increase the need to control surface water drainage to manage flooding and its impact on communities.

Water is vital to the preservation of green spaces and water demands are strongly influenced by the climate conditions (precipitation, temperature, humidity and evapotranspiration) that affect the hydrologic cycle and water availability. Evapotranspiration from green spaces helps to reduce the urban island effect, but this only works if green areas are kept green, otherwise just when evapotranspiration is most needed, it fails. Green areas also create spaces that harvest, clean and recycle water.

By helping to manage the urban water cycle as a whole, a more efficient use of resources can be achieved, not only providing economic benefits but also improving social and environmental outcomes. Water sensitive cities are resilient, livable, productive and sustainable.

According to Blinda (2012), ‘The theoretical average (for Mediterranean region) efficiency is estimated at between 40 and 60% for feed-surface irrigation, 70–80% for sprinkler irrigation and 80–90% for localized irrigation. Losses by evaporation and infiltration are highest under traditional (gravity-fed) surface irrigation.’ Portugal has a typical Mediterranean climate and it is included in this biome.

The aim of this study was to assess the contribution of water from the unprotected spring water source of Quinta da Rainha to the sustainable water management of the Botanical Garden of the University of Coimbra (BGUC), in Portugal, in response to the impacts of climate change as Portugal is in a vulnerable zone. In fact, as is related by the Intergovernmental Panel on Climate Change (IPCC 2007, 14 pp.), ‘In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability…’, ‘It is also projected to increase health risks due to heatwaves, and the frequency of wildfires.’ Additionally, it is our aim to highlight the importance of this source for the irrigation of the BGUC, as part of a global water management plan, when the increment of urbanized areas and some constructions compromise this important source.

MATERIAL AND METHODS

Study site

The BGUC dates back to 1772. It was built to study botany and its usefulness in medical and pharmacy studies.
The Garden occupies a total area of 13.5 ha and it is divided into two fundamentally different parts: the area open to visitors, laid out on three terraces that form an amphitheatre, dominated by a harmonious blend of exotic trees, native shrubs and small plants representing the taxonomic families found in Portugal, in a setting of diverse architectural structures. It occupies an area of around 5 ha, and the wooded area mostly consists of mixed forest where essentially exotic trees from Australia and South America have adapted perfectly; and trees crucially provide shade, evaporative cooling, pollution filtration and also capture and store carbon (Nowak 2006; Nowak et al. 2006). Over 2,000 plant species have been registered and their specific location will soon be available at http://www.uc.pt/jardimbotanico.

Due to its enormous surface just from construction the question of water needs was addressed and several different spring water sources were allocated for this purpose. Unhappily some of them were destroyed with the growth of the city or used for other purposes. The only one that remains with the original objective is that dating back to its construction in 1798.

The BGUC (Figure 1) is an open public space in the central area of Coimbra that enriches the city’s quality of life, serves the recreational needs of visitors and offers them a fascinating journey through the world’s flora.

The BGUC represents about 8% of all public green spaces in the urban area of Coimbra and is the second largest green area. If we consider only the inner urban area, then the Botanical Garden represents 26%, which underlines its ecological value and contribution to the city of Coimbra (Cunha 2007).

In geological terms, the district of Coimbra is situated between the Hesperian (or Iberian) Massif, consisting of Precambrian Paleozoic formations, and the western Meso-Cenozoic sedimentary deposits (Tavares 1999). The Botanical Garden is in a zone of dolomite marl and Triassic red sandstone. In hydrogeological terms they are characterized by compact formations of variable low permeability, although it may be higher where there is fracturing.

The water needed for irrigation mainly comes from a source located 1,000 m away (Figure 2). The water is conducted to the Botanical Garden via gallery sections (a semi-circular channel section, 8 cm in height and 12 cm wide) and pipes (φ 75 mm in cast gray iron) in a free surface flow, ending in a large reservoir with a volume of 445 m³ located at the top of BGUC. Major demands can be provided by the mains water system or from a 123 m deep well, constructed for the purpose.

**Climate records**

The climatological data were obtained from two meteorological stations. One is the Geophysical Institute, part of the University of Coimbra, with daily records from 2000 to 2009; it is located at coordinates 40°1′ N, 08°25′ W, 139.6 m altitude, and 500 m from the Botanical Garden (http://www1.ci.uc.pt/iguc/). The other is the Bencanta meteorological station (40°12′ N, 08°27′ W, 35 m above sea level), which is 3,500 m from the Botanical Gardens (http://www.meteo.pt/).

These data enabled the mean annual rainfall and temperature to be calculated for the period 2000–2009, yielding figures of 647 mm and 15.8°C. The average minimum
temperature was 11.5 °C and the average maximum temperature was 21.5 °C.

Two longer periods were also used, but only for mean values and only from the Geophysical Institute. The figure for annual precipitation published by the Geophysical Institute was 1,013 mm, with 141 days of precipitation. The annual average temperature was 14.9 °C, with the average minimum being 10.4 °C and the average maximum 21.1 °C.

In the period 1971–2000 the average annual rainfall was 975 mm, with 138 days of precipitation. The annual average temperature was 15.1 °C, with 10.7 °C being the average minimum and 21.0 °C the average maximum temperature. Even though this is not sufficient to draw hard and fast conclusions, a tendency for lower rainfall and higher temperatures can be observed. Table 1 summarizes the climatic conditions.

Table 1 | Mean climate conditions

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<tr>
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<tr>
<td>Total precipitated (mm)</td>
<td>1,013.6</td>
<td>975.0</td>
<td>647.0</td>
</tr>
<tr>
<td>Average temperature (°C)</td>
<td>14.9</td>
<td>15.1</td>
<td>15.8</td>
</tr>
<tr>
<td>Mean maximum temperature (°C)</td>
<td>22.1</td>
<td>21.0</td>
<td>21.5</td>
</tr>
<tr>
<td>Mean minimum temperature (°C)</td>
<td>10.4</td>
<td>10.7</td>
<td>11.5</td>
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Sampling, measuring and calculating

To assess the sustainability of the water management used to irrigate the BGUC we analysed the climate data, the availability of water from the spring water source, and the records of the mains water supplied.

As stated earlier, only part of the Botanic Garden is open to the public (about 5 ha) and only this area is irrigated. Therefore, this study only focussed on this area. The rest is forest and a small orchard and are not considered in this study for the purpose of water balance.

The spring water collector output, the water storage capacity in the Garden and the ability to use water from rainfall and/or infiltration were also assessed.

Knowledge of the soil water balance is essential to characterize the groundwater reserves over the year; estimating actual evapotranspiration and quantitatively assessing the periods of soil water shortage or surplus help to identify inefficiency and opportunities for improving the management and sustainable use of water for irrigation.

The water balance model analyses the allocation of water to the various components of the hydrologic system by means of a monthly accounting procedure that is based...
on the method originally presented by Thornthwaite (cited by McCabe & Markstrom (2007)).

Inputs to the model are mean monthly temperature ($T$, in degrees Celsius), monthly total precipitation ($P$, in millimetres), and the latitude (in decimal degrees) of our location. The latitude of the location is used to compute day length, which is needed to calculate potential evapotranspiration (PET).

The concept of water balance developed by Thornthwaite considers the soil as a fixed reservoir in which the water is stored up to a maximum of field capacity and is only removed by the action of plants.

Using climatic variables such as precipitation ($P$) and temperature ($T$), the model, modified by Thornthwaite and Mather in 1955 to make it more useful for a wide range of soils and plants, can be used to estimate evapotranspiration (PET). The soil water holding capacity (SWC), which represents the maximum storage of water in the soil, enables the climatic water balance to be calculated, which in turn will determine the actual evapotranspiration, any shortage or surplus water, and the total water retained in the soil in each period.

In addition, the analysis of the Gaussen ombrothermic diagram and climatic water balance enables dry and wet periods to be determined, thus providing a rough idea of the water demands and changes in the soil’s water storage capacity.

Thornthwaite proposed the following equation to calculate evapotranspiration:

$$\text{PET} = 16 \left( \frac{10}{T_i} \right)^a$$

where $T_i$ is the average air temperature (greater than 0 °C) for each month and $J$ is the annual heat index, as calculated by Equation (2):

$$J = \sum_{i=1}^{12} (0.2 T_i)^{1.514}$$

$a$ is a constant given by:

$$a = 6.75 \times 10^{-7} J^3 - 7.7 \times 10^{-5} J^2 + 1.7912 \times 10^{-2} J + 0.49239$$

In gardens, parks and green areas in general, the purpose of irrigation is not to give the plants all the water needed to compensate for all losses, but simply to give them enough to let them develop and keep them healthy and looking good.

The amount of water needed for this is estimated by means of two expressions (Costello et al. 2006).

The Landscape Evapotranspiration formula:

$$\text{ET}_L = K_L \cdot \text{ET}_0$$

and the Landscape Coefficient $K_L$ formula:

$$K_L = k_s \cdot k_d \cdot k_{mc}$$

$k_s$ – species factor (dimensionless); $k_d$ – density factor (dimensionless); $k_{mc}$ – microclimate factor (dimensionless); $\text{ET}_0$ – reference evapotranspiration (mm/period).

The total water needed in 1 day is (TWA):

$$\text{TWA} = \frac{\text{ET}_L}{\text{IE}}$$

where IE is the efficiency of irrigation.

**RESULTS**

The climatic data analysis shows some irregularity in the rainfall regime. 2004 and 2005 were very dry years when the total annual precipitation was 490 mm and 333 mm, respectively, figures that are much lower than the normal values for the period.

Figures 3 and 4 show the climatic water balance and Gaussen diagram for normal climatological values for 1961–1990.

Figures 5 and 6 present normal climatological values for 1971–2000, and Figures 7 and 8 give the corresponding values for the period 2001–2009.

Figures 9 and 10 present the average monthly temperatures and precipitation for the years 2000–2009.

Figures 9 and 10 show some irregularities in temperature and precipitation when we compare their values with those of the normal climate periods of 1961–90 and
1971–2000. However, the months of May to September are still those in which there are simultaneously the highest values for temperature and evapotranspiration, and the lowest values of precipitation. This is the period when irrigation demands are greatest.

To estimate the availability of water supplied by the spring water collector in terms of its quantity and quality,
flow measurements (volumetric method) and water samples were taken. The results are presented in Table 2.

It can be seen that the water quality meets the conditions for irrigation purposes (Portuguese law, DL 236/98, transposing European Directive 98/83/CE).

In the year and month with the highest evapotranspiration (123 mm, August 2005), considering an irrigation efficiency of 70%, and a surface of 5 ha, the total water to apply (TWA) stands at 16,500 L/day.

However the existing automatic irrigation system has a discharge value of 4 L/s and an irrigation period of 5 hours, which, together with other needs such as aesthetic and environmental requirements, accounts for a volume of 95,500 L/day, and clearly exceeds the output of the spring water source.

Dividing the value of TWA by the total volume (V) of water used for irrigation, the value obtained for efficiency (E = TWA/V) is, in this case, of the order of 17%, which can be considered too low.

The volume of a reservoir needed to address differences between inflows and outflows can be obtained by Equation (7):

\[
V = \max \left( \sum_{i=1}^{n} Q_i(t) - \sum_{i=1}^{m} Q_0(t) \right) - \min \left( \sum_{i=1}^{n} Q_i(t) - \sum_{i=1}^{m} Q_0(t) \right)
\]

where \( Q_i(t) \) are inflows, from different origins, and \( Q_0(t) \) are outflows for different purposes, at different times.

Figures 11 and 12 represent this balance graphically in a dry and a normal year, and the lack of water in these situations can be seen.

In Figures 11 and 12, AV and AC are the total volume entering and outgoing daily and it can be seen that the deficits are 32.4 m³ for a dry year and 14.3 m for a normal year.

To solve this problem of a water deficit a well was constructed, after which all needs were satisfied.
To achieve this goal it would be necessary to pump for a period of 4 hours, with a discharge of 2.3 L/s in a dry year, and 1.0 L/s in a normal year (Figures 13 and 14).

The volumes needed to make that possible are 45.6 m³ for the dry year and 36.0 m³ for the normal year, and they are far below the existing volume of the reservoir, 445 m³.

In the past, to overcome the lack of water it was necessary to draw on the public water supply system. But since 2008, when this study began, frequent cleaning of the channel that carries the water from the spring water source has led to certain improvements and, as can be seen from the graph in Figure 15, the consumption of public water supply was drastically reduced.

**CONCLUSIONS**

From the analysis of the climate data and the calculations, it is clear that the driest months are July and August, when only about 3% of annual rainfall is recorded, and the period of the highest evapotranspiration is from April to September, when the deficit can be 123 mm (in August 2005).

It should be emphasized that in 2004 and 2005 there is no surplus of water in the soil, making them exceptionally dry years with an annual rainfall of 490 mm (2004) and 332 mm (2005) and only 76 and 74 days of precipitation, respectively.

Measurements taken from the spring water source support the conclusion that it is possible to provide an average annual volume of 30,000 m³, regardless of the characteristics of the rainfall regime, and this largely exceeds the demand.

Furthermore, with the volume of the existing reservoir (445 m³) and without pumping water from the well it will be possible to last for a period of 13 days, in a dry year, and 31 days in a normal year, if the irrigation values are unchanged.

From this study, we can conclude that in the BGUC, and certainly in many other parks and green urban areas of Coimbra, a better approach to the irrigation systems is needed. In the BGUC, considering that the amount of water needed is only that of evapotranspiration, Equation (6), the efficiency is very low and less than 20%. However, it is also important to take into account the need to use soil and water in a balanced way, and consider other indirect services, such as aquifer recharge provided by surface irrigation.

The use of other sources of water for irrigation at BGUC (spring water source and well) allowed consumption from the public water supply system (treated water, more
expensive and not as good for watering plants) to be eliminated, which helped to improve the economic aspect of sustainability. Even allowing for the fact that water which is not absorbed by plants, evaporates or infiltrates, and that helps the natural hydrological cycle, it is clear that more has to be done to improve the efficiency of irrigation.

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