Assessment of water and energy efficiency in urban and historical gardens

Raquel Rebelo Cristina
rrc_1996@hotmail.com
Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

Water and energy consumption in urban gardens has not yet been extensively studied, although considerable amounts of water and of associated energy are consumed in these green areas. The aim of the current thesis is to develop and apply a methodology to evaluate the water and energy consumption in urban and historical gardens. The methodology is based on water and energy balances and the associated performance indicators, adapted from the already existing balances for water supply systems and for collective irrigation systems. The proposed balances include new components, such as the landscape water requirements, which is the theoretical plants water needs. These balances are applied to three case studies of different nature and characteristics: the gardens of the National Palace of Queluz (a historical garden), Vale do Lobo urban gardens (a modern garden with a smart irrigation system) and Marechal Carmona urban park (a garden with traditional irrigation system and recreational uses). The water balances allow to estimate and to compare yearly water consumption in the case studies and to assess the importance of other water uses. The application of the water balance to consecutive years allows assessing the effectiveness of implemented measures for water demand reduction. Results show that the historical gardens consume less water than the modern ones and that the implementation of smart irrigation systems effectively reduce water consumption in modern urban gardens. The application of the energy balance allows assessing the impact of water efficiency measures on energy efficiency and demonstrates that the historical gardens are more energy efficient than the modern ones. The proposed methodology can be applied to gardens with different water uses, for the evaluation of the water and energy consumption and for the identification of water and energy use improvement measures.

Keywords: gardens, water balance, energy balance, efficient water use, landscape water requirement, water losses.

1 Introduction

Water is a limited resource and its use should be carried out as efficiently as possible. Without it no society can thrive, due to its importance for socio-economic development, energy and food production (Lopera et al., 2015). Furthermore, global population growth demands higher water use and the same amount of water availability worldwide needs to be balanced between all the growing population, services and commercial uses. If water use is not done properly, it is not possible to guarantee water availability to everyone in the near future (Arnell et al., 2016).

In the cities, the urban gardens are water intensive consumers either for recreational purposes or for the irrigation of green areas. This sector needs to use water wisely and to decrease water waste. Urban gardens can account for about 50 to 60% of the water consumed by municipalities, such as the case of Lisbon and of Cascais (*Lisboa e-nova, 2014 & Covas et al., 2019*). These are very high percentages that show the importance of the water use in public gardens in the overall water consumption in the cities. Similar situations can be expected in other cities with significant green areas. Indeed, public gardens are a relevant sector in terms of amount of water consumption and energy used.

The principal aim of this research is the development and application of a methodology to assess water and energy efficiency in urban and historical gardens. The methodology is based on the water and energy balances proposed for urban water supply systems, adapted for water and energy use in gardens with the proposal of calculation of the new components. New components of the water balance include calculation of the theoretical plants water needs, estimation of water consumption for other uses besides irrigation and consideration of evaporation losses, deep percolation to the soil layers and runoff as a percentage of water losses. The new components of the energy balance include the estimation of minimum energy for irrigation and for other uses. The proposed water and energy balances are applied to three different real case studies, from the historical 18th century garden to the most modern garden with smart irrigation systems and the obtained results are discussed accordingly.

2 Methodology

2.1 Water balance calculation

A novel water balance for assessing water consumption in gardens and urban green areas is developed (Figure 1), based on proposed water balances for water supply systems (Lambert and Hirner, 2000) and for the collective irrigation systems (Cunha, 2018).

System input volume (network water supply, underground sources, reclaimed water or harvested rainwater)	Effective consumption	Consumption for irrigation	Irrigation needs (LWR)
		Consumption for other uses	Uses in toilets, restaurants
			Uses in fountains
			Lakes filling
	Water losses	Apparent losses	Unauthorised consumption
			Metering inaccuracies
		Irrigation losses	Evaporation losses, deep percolation to the soil layers and runoff
		Network real losses	Leakage in the irrigation network
			Leakage in canals and in intermediate reservoirs

Figure 1 Components of the water balance for gardens (m^3/year).

System input volume

The first step in the construction of the water balance is to identify the subcomponents of the system input volume. The system is frequently supplied from the drinking water network or from underground sources, although other alternative water sources, such as reclaimed water or harvested rainwater can also be used. Supply water volumes should be preferentially metered, or estimated as precisely as possible, by the utility in charge of the garden management. This value should be quantified or estimated as precisely as possible since it is the starting point of the water balance calculation.

Effective use

Effective water use is the second component of the balance to be calculated. This is divided into two subcomponents: consumption for irrigation and consumption for other uses.

The consumption for irrigation corresponds to the landscape water requirement, LWR, which can be calculated by (USEPA, 2009):

$$LWR = \frac{1}{DU_{LQ}} x[(ET_0 x K_L) - R_a] x A \qquad [1]$$

where LWR is the landscape water requirement (m^3/year), DU_{LQ} is the lower quarter distribution uniformity (dimensionless), ET_0 is the reference evapotranspiration (mm/month), K_L is the landscape coefficient for the type of plant (dimensionless), R_a is the allowable rainfall (mm/month) and A is the irrigated area (m^2). The distribution uniformity values, DU_{LQ}, depend on the type of irrigation (sprinkler or microirrigation), while K_L values depend on the type of plant. Reference values for both coefficients can be found in the literature (USEPA, 2009). Reference daily or monthly values for evapotranspiration and precipitation can be taken from the nearest meteorological station, depending if the LWR is calculated monthly or daily. A similar approach was used by Ruíz-Pérez et al. (2020) to obtain the garden water requirements using the concepts of evapotranspiration and the landscape coefficient (Ruíz-Pérez et al., 2020).

The consumption for other uses in the garden should be quantified. Ideally, irrigation networks and water supply networks to facilities inside the gardens (i.e., WCs, restaurants, fountains) should be independent, each one with its own flowmeter. Usually, the two networks are not separated and the water consumptions for the other uses must be estimated. These can be estimated if diurnal consumptions are known, when there is no irrigation, discounting the water losses.

Water losses

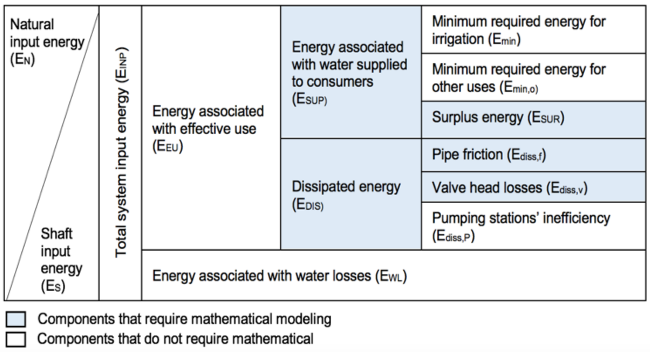
Water losses include all the irrigation losses, the apparent losses and the network real losses. The water losses can be obtained by the difference between system input volume and the effective use.

Irrigation real losses include all the water that is consumed in irrigation but that is more than needed to fulfil the plants' requirements. Such water is loss due to evaporation, percolation through soil and surface runoff. Because it is very hard to estimate each of these irrigation losses, this component is estimated as a whole by calculating the difference between the system input volume and the sum of effective use, apparent losses and network real losses. Similarly to the water balance proposed for the urban water supply systems and the collective irrigation systems, apparent losses in irrigation systems include unauthorised consumption and metering inaccuracies. Unauthorised consumption regards to water thefts and illegal connections to the irrigation system. If detected by the garden workers, it can be estimated by multiplying the duration of the event by the probable flowrate. Metering inaccuracies can be estimated based on the characteristics of the metering devices, i.e., the irrigation meters installed at the systems entrances.

Network real losses include the subcomponents of leakage in the irrigation network and leakage in canals and in intermediate tanks. Leakage in the irrigation network can be estimated by Minimum Night Flow Analysis (MNF), which consists of analysing the minimum water flowrate in the system when there is no irrigation or consumption for other uses. Background leakage is frequent in pressurized systems and can be estimated by applying Burst and Background Estimates (BABE) and the top-down water balance, which are methods that do not require field-based methods, as opposed to MNF method (AL-Washali et al., 2016). The last component of the balance, leakage in canals and in intermediate tanks, when such infrastructures exist in the irrigation system, can only be estimated as the difference between the total network real losses and the leakage in the pressurized irrigation network.

2.2 Energy balance calculation

An energy balance specific for gardens and urban green areas is developed (Figure 2), based on the energy balance proposed by Mamade (2019). Components highlighted in light blue require mathematical modelling to be calculated, whereas components not highlighted do not require any mathematical modelling.



Natural input energy (E_N) Shaft input energy (E_S)	Total system input energy (E_{INP})	Energy associated with effective use (E_{EU})	Energy associated with water supplied to consumers (E_{SUP})	Minimum required energy for irrigation (E_{min})
				Minimum required energy for other uses ($E_{min,o}$)
				Surplus energy (E_{SUR})
			Dissipated energy (E_{DIS})	Pipe friction ($E_{diss,f}$)
				Valve head losses ($E_{diss,v}$)
				Pumping stations' inefficiency ($E_{diss,P}$)
		Energy associated with water losses (E_{WL})		

▨ Components that require mathematical modeling

☐ Components that do not require mathematical

Figure 2 Proposed energy balance in gardens and urban green areas (kWh).

Total system input energy

Total system input energy is the sum of the energy that is supplied to the system by its various water sources. Natural input energy, E_N, corresponds to the potential energy supplied by reservoirs, storage tanks or pressurized delivery points at the inlet of the system. In most irrigation systems natural, input energy is referred only as pressurized energy delivered by the municipal water distribution network. Shaft input energy, E_S, is associated with energy supplied by all the pumping stations existing in the irrigation system. The sum of these two energy sources leads to total system input energy, E_{INP}, which is divided into energy associated with effective use, E_{EU}, and energy associated with water losses, E_{WL}.

The total system input energy, $E_{IN,}$ can be calculated, as follows, in case there are not pumping stations in the system:

$$E_{INP} = \frac{\gamma\ V_{consumed}\ H_{app}}{3600*1000} \qquad [2]$$

in which E_{INP} is the total energy input (kWh), γ is the specific weight of water (N/m^3), $V_{consumed}$ is the water volume consumed in irrigation plus the losses (m^3) and H_{app} is the pressure head supplied to the irrigation system (m). The pressure head can be obtained as follows:

$$\mathrm{H_{app}} = \mathrm{Z_e} + \frac{\mathrm{P_{inlet}}}{\gamma} - \mathrm{Z_0} \qquad [3]$$

in which Z_e is the elevation of the node at the inlet of the irrigation system (m), P_{inlet} is the pressure at the inlet of the irrigation system (Pa) and Z_0 is the reference elevation or the node of minimum elevation in the irrigation system (m).

Energy associated with effective use

Energy associated with effective use includes the energy that is effectively supplied to the consumers along with the water, E_{SUP}, and all the energy that is dissipated in the system, E_{DIS}.

The energy associated with the water supplied to consumers includes the minimum required energy for irrigation, E_{min}, the required energy for other uses, $E_{min,o}$, and the surplus energy, E_{SUR}. The first can be obtained from the theoretical minimum operating pressure, given by the manufacturer of the irrigation equipment. It depends on the type of sprinkler or dripper/micro-sprinkler. The second one is related with the minimum pressure requirements at the consumption point for the other water uses.

Minimum required energy, either for irrigation or other uses, can be calculated as follows:

$$E_{min} = \frac{\sum_{i=0}^{n} \gamma \, V_{theoretical,i} \, Hmin_i}{3600*1000} \qquad [4]$$

in which E_{min} is the minimum required energy (kWh), γ is the specific weight of water (N/m^3), $V_{theoretical,i}$ is the theoretical water consumption at node i (m^3) and $H_{min,i}$ is the minimum pressure head in each irrigation node i (m), given by:

$$H_{min,i} = Z_i + \frac{P_{min}}{\gamma} - Z_0 \qquad [5]$$

in which $H_{min,i}$ is the minimum pressure head at each nodes i (m), Z_i is the elevation of node i (m), P_{min} is the minimum required operating pressure (Pa), Z_0 is the reference elevation or the node of minimum elevation in the irrigation system (m).

The surplus energy, E_{SUP}, corresponds to the energy above the minimum required that is supplied at the node level. Dissipated energy in the water supply systems of the gardens is due to pipe friction, valve head losses and the pumping stations' inefficiency, if wells or boreholes exist. Dissipated energy due to pipe friction and valve head losses can only be estimated using mathematical modelling.

Energy associated with water losses

The last component of the balance, energy associated with water losses (E_{WL}), if approached using the top-down methodology, can be obtained by associating the water losses percentage from the water balance as proportion to the energy associated with water losses, as follows:

$$E_{WL} = E_{INP} * WL/100 \qquad [6]$$

where E_{WL} is the Energy associated with water losses (kWh], E_{INP} is the total system input energy (kWh) and WL corresponds to the percentage of water losses from the water balance (%).

2.3 Energy Performance indicators

Three energy performance indicators, E1, E2 and E3, can be calculated from the energy balance (Mamade et al., 2014). Performance indicator E1 represents the energy in excess per volume of consumed water:

$$E_1 = \frac{E_{INP} - E_{min}}{V_{consumed}} \quad [kWh/m^3] \qquad [7]$$

This ratio allows the evaluation of the potential of energy reduction per cubic meter of the water volume that enters into the system. It is always positive and should be as low as possible. The consumed volume includes effective uses and water losses.

Performance indicator E2 represents the energy in excess per unit of water needed for the irrigation (taken from the water balance, LWR):

$$E_2 = \frac{E_{INP} - E_{min}}{V_{theoretical}} \quad [kWh/m^3] \qquad [8]$$

This ratio allows the evaluation of the potential of energy reduction per cubic meter of water effectively used. This indicator should also be the lowest as possible and is always positive. It is preferred to use this indicator than E1 because E2 considers the water effective use in the denominator, which allows the assessment of water losses on the energy efficiency of the system. If the real losses of the system are reduced, E2 will be lower (i.e., numerator decreases because less total input energy is supplied and the volume of water effective use in the denominator stay the same, resulting in a lower E2 value).

Performance indicator E3 is the ratio of the input energy that is supplied to the system in comparison to the minimum energy required; it is a dimensionless ratio described by:

$$E_3 = \frac{E_{INP}}{E_{min}} \qquad [9]$$

This ratio allows the quantification of the energy in excess provided to the system compared with the minimum energy required. This ratio should be as low as possible, but it cannot be lower than one.

2.4 Calculation of the proposed energy balance using mathematical modelling

BEEPANET software application allows the calculation of all the subcomponents of the proposed energy balance. The program, developed in C++ language by Mamade (2019), uses the EPANET library and computes all components of the energy balance associated with a hydraulic model. In addition, some other information related with the system needs to be specified, such as the reference elevation, the water loss percentage, the minimum required pressure head and the energy mix. The analysis can be carried out yearly or monthly.

After the garden network is uploaded as an INP file and all the initial data are inserted, the energy balance is obtained. The energy balance results are obtained in kWh and in percentage of total input energy. The BEEPANET tool is still under development in CERIS.

3 Case study 1: Historical gardens of the National Palace of Queluz

3.1 Location and characteristics

The National Palace of Queluz and its gardens (Figure 3) are located in Queluz, a city in Sintra Municipality, in the Lisbon District, Portugal. The palace is surrounded by several natural water sources (e.g., springs, streams) which must have been one of the main reasons why this location was chosen for building the palace.

A complex hydraulic system was built at the National Palace of Queluz to transport water from the palace surroundings and to distribute the water to the numerous fountains and cascades of the gardens. This system included aqueducts and buried pipes that transported water from springs and streams nearby the palace area. The water was conveyed by gravity due to the difference in elevation between the water sources and the palace.

This case study represents an example of a historical garden in which the use of water was mostly for aesthetic means. In this type of garden, the species used require very few or none water, being composed of trees and shrubs. No turfgrass was used, which is one of the species that requires more irrigation. There was not a modern piped water system or pumps available like in today's modern years, which made it mandatory to construct gravitational water systems capable of collecting water and transport it to its destination. Consequently, the water use was carefully studied in the sense that it would flow to the fountains and cascades and, later, it was reused for irrigation. Gardens, nowadays, prevail from these modern systems and, therefore, can be built based on a different architecture; the water use is basically for irrigation and less for aesthetics because the plants species in the modern gardens require irrigation. The National Palace of Queluz gardens are used to illustrate the application of the proposed methodology to calculate the energy balance.


(a) (b)

Figure 3 Selected fountains and cascades from the gardens of the National Palace of Queluz (a) Medallions fountain, (b) Great cascade

3.2 Hydraulic modeling

The water supply system of the gardens of the National Palace of Queluz are composed of three independent pressurized subsystems (Curro, Miradouro and Quatro Bicas). The network systems were drawn in AutoCAD 2020 and converted into an EPANET model (Rossman, 2000).

Each of the subsystems is composed of one source tank with constant head, a set of pipes with constant diameter and junction/extreme-end nodes with assigned water demand. This demand was specified according to the fountain/cascade type (I or II) and to the demand scenario analysed (1, 2 or 3).

Type I is associated with smaller lake surface area (between 3 and 55 m^2) and few water spurts (less or equal than four). Type II is associated with a larger area (higher than 55 m^2) and/or higher number of water spurts (more than four). Cascades were also considered Type II due to their large size.

Three demand scenarios were established and analysed (Table 1) to quantify the water consumed in the gardens for ornamental purposes only, based on known water flowrates at the domestic level.

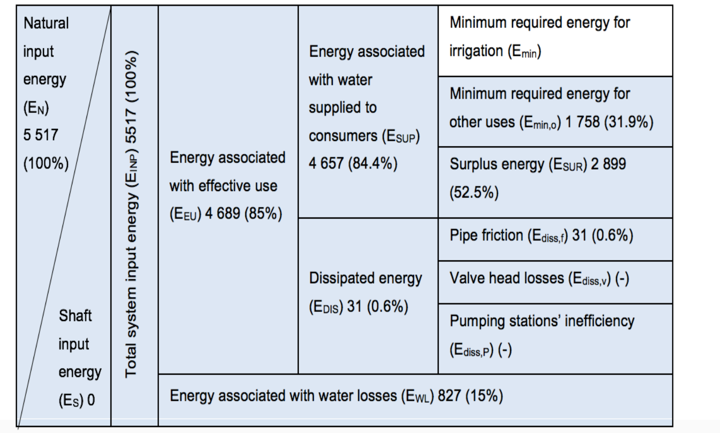
Table 1 *Water demand at the fountains in each of the three scenarios.*

Scenario	**Water demand at the fountains (L/s)**	
	Type I	**Type II**
S1	0.5	0.8
S2	1.0	1.3
S3	2.0	2.3

3.3 Application of the proposed energy balance

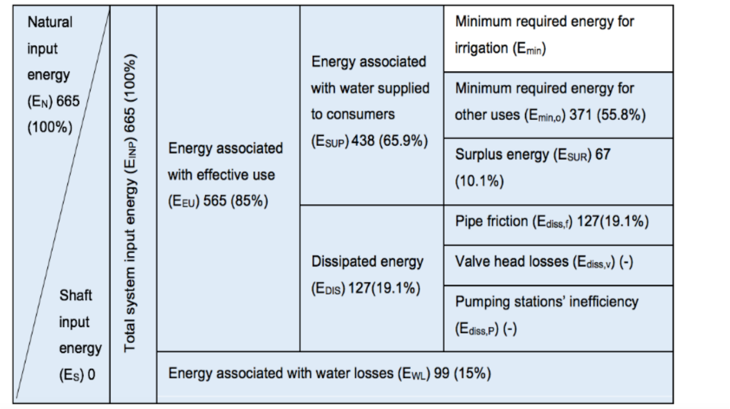
After modeling the subsystems in EPANET the energy balances are calculated for all of them by using the BEEPANET. Initial values for the input variables are set for each subsystem. Reference elevation is the minimum elevation in each subsystem, i.e., in Curro subsystem 94 m corresponds to the elevation of the

fountain with the minimum elevation. The same methodology is applied to the other two subsystems.
The minimum required pressure head corresponds to the minimum required water height at the fountains, in meters, in each subsystem.
The energy balances for the simpler subsystem (Curro) and the most complex (Miradouro) are presented in Figures 4 and 5.



Natural input energy (E_N) 5 517 (100%)	Total system input energy (E_{INP}) 5517 (100%)	Energy associated with effective use (E_{EU}) 4 689 (85%)	Energy associated with water supplied to consumers (E_{SUP}) 4 657 (84.4%)	Minimum required energy for irrigation (E_{min})
				Minimum required energy for other uses ($E_{min,o}$) 1 758 (31.9%)
				Surplus energy (E_{SUR}) 2 899 (52.5%)
			Dissipated energy (E_{DIS}) 31 (0.6%)	Pipe friction ($E_{diss,f}$) 31 (0.6%)
				Valve head losses ($E_{diss,v}$) (-)
Shaft input energy (E_S) 0				Pumping stations' inefficiency ($E_{diss,P}$) (-)
		Energy associated with water losses (E_{WL}) 827 (15%)		

Figure 4 *Energy balance of the Curro subsystem (kWh/year).*



Natural input energy (E_N) 665 (100%)	Total system input energy (E_{INP}) 665 (100%)	Energy associated with effective use (E_{EU}) 565 (85%)	Energy associated with water supplied to consumers (E_{SUP}) 438 (65.9%)	Minimum required energy for irrigation (E_{min})
				Minimum required energy for other uses ($E_{min,o}$) 371 (55.8%)
				Surplus energy (E_{SUR}) 67 (10.1%)
			Dissipated energy (E_{DIS}) 127(19.1%)	Pipe friction ($E_{diss,f}$) 127(19.1%)
				Valve head losses ($E_{diss,v}$) (-)
Shaft input energy (E_S) 0				Pumping stations' inefficiency ($E_{diss,P}$) (-)
		Energy associated with water losses (E_{WL}) 99 (15%)		

Figure 5 Energy balance of the Miradouro *subsystem (kWh/year).*

Curro subsystem presents the lowest minimum required energy (as percentage of the input energy) and the highest percentage of surplus energy, when compared with the other subsystems. This means that the difference in elevation between the Curro reservoir and the fountains of this subsystem is higher than needed, i.e., there is more than enough energy to produce water jets in both fountains. In the case of Miradouro subsystem, the surplus energy percentage is the smallest (10.1%), meaning that the difference in elevation between the Miradouro tank and the fountains is just enough to produce the water jets at the fountains and only a small fraction of energy is in excess.

It is important to refer that the water consumption at each fountain is based on assumptions because the water consumption of the fountains in the eighteen century is unknown. These results show that the three subsystems were designed and built in order to make the water spurts operate in all the fountains and cascades present in the National Palace of Queluz.

4 Case study 2: Vale do Lobo urban garden

4.1 Case study descriptions

Empresa de Infraestruturas de Vale do Lobo, E.M., Infralobo, is a water utility located in Vale do Lobo, a touristic resort in Loulé Municipality, in the Algarve region. This case study is focused on a specific urban garden of 1.92 ha, which corresponds to around 9% of all the green spaces managed by Vale do Lobo. There are twenty irrigation meters, each of them serves more than one green space. The characteristics of each green space differ: they can either be a turfgrass area or a flower bed area. In total, the garden comprises 154 green spaces (both turfgrass and flower bed).
With the aim of optimizing the irrigation system, Vale do Lobo utility implemented a personalized platform, named "Smart Irrigations System" (SIS). This solution allows the measurement of rainfall via a meteorological station installed in the area and the adjustment of the irrigation needs in the 22 ha of green spaces, according to the atmospheric conditions, making the system operation automatic. In this sense, there is a continuous optimization of the irrigation schedules, depending on the weather conditions, shutting off irrigation if the weather conditions justify it.

4.2 Application of the proposed water balance

The proposed methodology for the water balance calculation in gardens and urban green areas is applied to Vale do Lobo case study, for the years 2017, 2018 and 2019.
Effective use is divided into consumption for irrigation and consumption for other uses, the last one being zero for this case study.
Consumption for irrigation is the amount of water that is needed to fulfil the plants water requirements (LWR). In Vale do Lobo case study, sprinkler irrigation is used for turfgrass areas and microirrigation for flowerbed areas. The used values for DU_{LQ} and K_L are presented in Table 2.

Table 2 Lower quarter distribution uniformity (DU_{LQ}) and landscape coefficient for the type of plant in the hydrozone (K_L) for the areas irrigated by sprinklers and by microirrigation (USEPA, 2009).

	DU_{LQ}	K_L
Sprinkler irrigation	0.70	0.7
Microirrigation	0.70	0.5

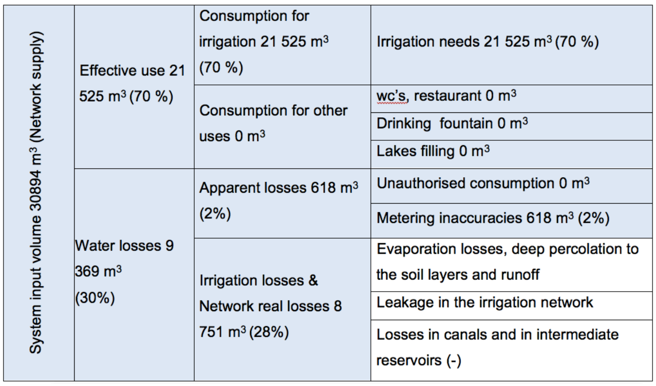
The Table 3 presents the landscape water requirements calculated for the three years. Calculated landscape water requirements are lower in the years of higher precipitation (the case for 2018), as expected. In 2019 the precipitation was lower which explains why in this year irrigation needs are the highest.

Table 3 Vale do Lobo irrigation system: effective use for the years 2017, 2018 and 2019 (m^3).

	2017	2018	2019
Landscape water requirements (m^3/year)	17 433	13 860	21 525

Water losses are divided into apparent losses, irrigation losses and network real losses. Apparent losses have, as subcomponents, unauthorised consumption and metering inaccuracies. Unauthorised consumption are considered zero because this is a resort with extremely high security. Metering inaccuracies are considered to be 2% of the system input volume for the three years. It is not possible to calculate in detail water losses due to irrigation losses and network real losses. The approach followed herein is to subtract apparent losses and effective use from the system input volume. The result represents the total of water losses due to evaporation, deep percolation, run off, as well as due to losses in the irrigation network.

Figure 6 shows the water balance for the year 2019, highlighted in blue are the components that could be calculated.



System input volume 30894 m³ (Network supply)	Effective use 21 525 m³ (70 %)	Consumption for irrigation 21 525 m³ (70 %)	Irrigation needs 21 525 m³ (70 %)
		Consumption for other uses 0 m³	wc's, restaurant 0 m³
			Drinking fountain 0 m³
			Lakes filling 0 m³
	Water losses 9 369 m³ (30%)	Apparent losses 618 m³ (2%)	Unauthorised consumption 0 m³
			Metering inaccuracies 618 m³ (2%)
		Irrigation losses & Network real losses 8 751 m³ (28%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate reservoirs (-)

Figure 6 *Water balance applied to Vale do Lobo for the year 2019.*

Obtaining the water balance for the reference periods (2017, 2018 and 2019) allows the quantification of the percentage of effective use and of water losses through time (Table 4). The water balance component “Effective use” is the percentage of water that was not wasted during irrigation. In 2019, this percentage was the highest: 70% of the supplied water was effectively used for irrigation. On the contrary, the percentage of water losses has diminished from 2017 to 2019, which means that more water was saved in 2019, as a result of the SIS implementation and of a greater awareness for the efficient use of water.

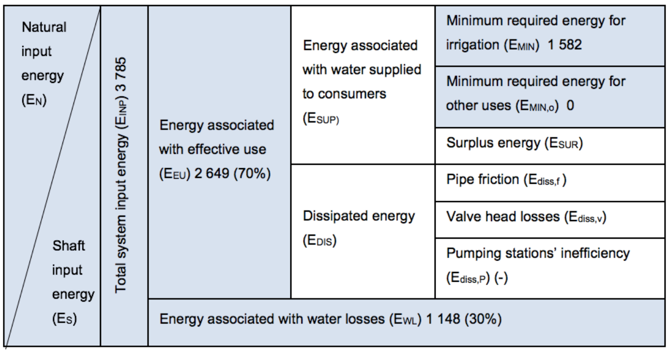
Table 4 Vale do Lobo irrigation efficiency: effective use and water losses for the water balance in the years 2017, 2018 and 2019.

	2017	2018	2019
Effective use (%)	55	57	70
Water losses (%)	45	43	30

4.3 Application of the proposed energy balance

The proposed methodology for the energy balance for urban irrigation systems is applied in Vale do Lobo case study, for the years 2017, 2018 and 2019. A top-down approach is carried out. Not all the components of the energy balance can be calculated, because some of them, as explained, require mathematical modelling, and there is no mathematical model available to analyse this system. It is possible to calculate the total system input energy, the minimum required energy and the energy associated with water losses.

Figure 7 depicts the energy balance for 2019, highlighted in blue the components that were able to be calculated.



Natural input energy (E_N) / Shaft input energy (E_S)	Total system input energy (E_{INP}) 3 785	Energy associated with effective use (E_{EU}) 2 649 (70%)	Energy associated with water supplied to consumers (E_{SUP})	Minimum required energy for irrigation (E_{MIN}) 1 582
				Minimum required energy for other uses ($E_{MIN,o}$) 0
				Surplus energy (E_{SUR})
			Dissipated energy (E_{DIS})	Pipe friction ($E_{diss,f}$)
				Valve head losses ($E_{diss,v}$)
				Pumping stations' inefficiency ($E_{diss,P}$) (-)
		Energy associated with water losses (E_{WL}) 1 148 (30%)		

Figure 7 *Energy balance for the year 2019 for Vale do Lobo irrigation system (kWh).*

Figure 8 compares the three energy performance indicators during the three years (2017, 2018 and 2019) in which the energy balance and water balance are calculated. The results demonstrate that the three energy performance indicators improve slightly from 2017 to 2019, leading to the conclusion that Vale do Lobo is using energy more efficiently. From the results presented in Table 4 this was expected, due to the decrease in water losses, which is directly connected with energy use.

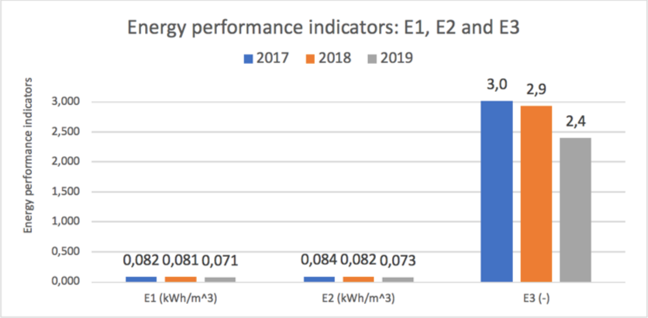


Figure 8 Energy performance indicators for Vale do Lobo.

5 Case study 3: Marechal Carmona urban park

5.1 Case study descriptions

Marechal Carmona is a public urban park located in the centre of Cascais. It has approximately 14 343 m^2 of irrigated area, of which about 11 100 m^2 correspond to turfgrass area with sprinkler irrigation, and the remaining 3 243 m^2 are covered with shrubs, herbaceous and flowers and are irrigated via microirrigation. In the park, there are also many trees, spread all over the park, small lakes, picnic areas, a field to play traditional games, cafes, wc's, museum, building for small conferences, municipal library for children and youth and a playground. The garden pipe network supplies water not only the for irrigation but also for other uses, such as for the public wc's, the drinking fountains, the small cafe and for filling and cleaning the lakes. There are five water meters in the park that measure all water consumptions in the park.

5.2 Application of the proposed water balance

In order to evaluate the water consumption in the park with more detail, a water balance for the years 2015, 2016 and 2017 is calculated using the proposed approach. The water balance for the year 2015 is presented in Figure 9, the calculated subcomponents are presented in light blue.

System input volume 47525 m^3 (14 258 m^3 Network supply and 33 268 m^3 Underground sources)	Effective use 41 685 m^3 (88 %)	Consumption for irrigation 17 164 m^3 (36 %)	Irrigation needs 17 164 m^3 (36 %)
		Consumption for other uses 24 521 m^3 (52%)	wc's, restaurant, drinking fountains and lakes filling
	Water losses 5 840 m^3 (12%)	Apparent losses 951 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 951 m^3 (2%)
		Irrigation losses & Network real losses 4 889 m^3 (10%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate tanks (-)

Figure 9 Water balance for Marechal Carmona park in 2015.

The park is supplied with water from the public distribution system as well as with water from underground sources, in approximately 30% and 70% respectively. Summing these two components corresponds to the system input volume. Potable water volumes consumed are given by the reading of the water meters in the park, while the volume of groundwater abstracted is estimated by the operators that manage the park. Results show that system input volume values are more or less constant for the three years.

Consumption for irrigation, LWR, is calculated for the three years using Equation 1. The monthly data for the evapotranspiration and precipitation are extracted from Instituto Português do Mar e da Atmosfera (IPMA) and the coefficients DU_{LQ} and K_L used to calculate LWR are the same as previously used (Table 2).

Regarding water consumption for other uses, variations in this subcomponent value are due to the several events that are carried out every year which directly affect water consumption (use of wc's and fountains, for instance). A year with more events will lead to a higher water consumption for other uses.

Water consumption for other uses needs to be accounted in the water balance because it is metered in the same meter that records water consumption for irrigation; in another words, irrigation network is not separated from the network that supplies water for the other uses. In order to estimate water consumption associated with other uses, it is considered that from November to February there is no irrigation, due to precipitation and all the consumption recorded during that period is exclusively due to other uses. However, in this way, the water losses during winter are also being accounted as consumption for other uses. Though this consumption is likely to vary over the year according to the events that occur in the park, consumption for other uses is considered constant in every month throughout the year. Ideally, this consumption should be measured by a specific meter.

The methodology to calculate water losses is the same as in the previous case study. Irrigation losses and network real losses are coupled, because it is not possible to calculate them separately. Apparent losses are also considered to be 2%, as in Vale do Lobo case study. Throughout the years, water losses do not vary too much (10 to 12% of the system input volume) and it seems there has not been any improvement from 2015 to 2017.

The balance shows that the highest percentage of water is spent on consumption for other uses. This is an urban park located in the centre of Cascais, where several people go every day, use the wc's, drink from the fountains an use the café. Additionally, the lakes existing in the park are also refilled using water from the irrigation network. However, consumption for other uses is likely to be overestimated, due to the lack of measured volumes.

Comparing this water balance to the balance from the previous case study, this illustrates a very different garden, in which water consumption for other uses is present and this subcomponent has a high weight on the overall water balance (42 to 50% of system input volume).

The percentages of the effective water use and of water losses are presented in Table 5. Effective use corresponds to the percentage of water that is effectively used both for irrigation and consumption by other uses. In the three years, the percentage of effective water use is considerably high (higher than 80%). The percentage of water losses is related with apparent losses, irrigation losses and network real losses and it is more or less constant during the three years (equal or less than 12%).

The estimated LWR is compared with the water consumed for irrigation and the irrigation efficiency is calculated (Table 6). The results show that the irrigation efficiency is satisfactory in 2015 and 2017 (60 ≤ IE < 80%) and adequate in 2016 (IE ≥ 80%).

Table 5 *Effective use and water losses for Marechal Carmona for the years 2015, 2016 and 2017.*

	2015	2016	2017
Effective use (%)	88	90	88
Water losses (%)	12	10	12

Table 6 *Consumption for irrigation, LWR and irrigation efficiency for the years 2015, 2016 and 2017.*

	Consumption for irrigation (m^3/year)	LWR (m^3/year)	IE (%)
2015	23 004	17 164	75
2016	18 852	15 854	84
2017	21 926	17 251	79

6 Case studies comparison

Three different gardens are studied. For these purpose, their yearly water consumption is calculated (Table 7).

For estimating the water consumption at the gardens of the National Palace of Queluz, it is assumed that all the fountains and cascades operated (with water spurts) during 6h every day of the year. An average consumption of the three scenarios is assumed. For Vale do Lobo and Cascais, it is also considered an average of the yearly water consumption. For Vale do Lobo case study, the average is calculated for 2017, 2018 and 2019 and for Cascais for 2015, 2016 and 2017.

Table 7 shows that the yearly water consumption in the historical garden of Queluz, per square meter, is much lower than in the urban park of Cascais and similar to that of the modern gardens of Vale do Lobo. Even though during the eighteen century, there were a lot of fountains and cascades in the gardens, consuming water for aesthetics reasons, water consumption was lower than that in the modern gardens were water is mostly consumed for irrigation, as well as for other purposes (cafés, wc's, lakes filling, etc). This might lead to the conclusion that, nowadays, urban gardens with irrigation consume a higher amount of water than in the past.

On the opposite, there is Marechal Carmona urban garden, which of the three is the one that consumes more water, per square meter and per year. It can be related with the high water demand for both other uses and irrigation or with the inefficient water use. The most likely hypothesis is that water consumption is high due to the high water demand of other uses and also due to high leakage levels.

The modern urban garden of Vale do Lobo has a yearly water consumption per square meter very similar to that of the gardens of the National Palace of Queluz. In this garden, water efficiency measures were applied and water consumption is strictly used for irrigation, contrarily to Marechal Carmona urban park.

Table 7 *Water consumption at the gardens of the Queluz National Palace, Vale do Lobo green areas and Cascais urban park.*

	Gardens of the Queluz National Palace	Vale do Lobo green areas	Cascais urban park
Water consumption ($m^3.m^{-2}.year^{-1}$)	1.4	1.5	2.8

Regarding energy efficiency, the historical gardens of Queluz are the most efficient, as the energy supplied to most of the fountains and cascades is only slightly higher than the minimum necessary energy. Also, the system is fully gravitational, that is, it operates with natural energy and, for that reason, it is the most sustainable garden. The Vale do Lobo gardens loose close to 40% of the energy that comes from the drinking water distribution network. This can be due to irrigation inefficiency and due to the dissipation of the excessive energy. However, the increase in irrigation efficiency also reduced the percentage of energy that was dissipated with the water losses, which demonstrates that water and energy efficiency in the gardens are closely related.

7 Conclusions and recommendations

7.1 Principal conclusions

A methodology to calculate water and energy balances for gardens is proposed followed by the application of this methodology in three case studies of different nature: the ancient gardens of the National Palace of Queluz (historical garden), Vale do Lobo urban gardens (modern garden with intelligent irrigation system) and Marechal Carmona urban park (garden with traditional irrigation system and recreational uses). The proposed balances are based on the existing balances for the urban water supply systems and for collective irrigation systems to which some changes are introduced to better tailor these balances for the water and energy uses in the gardens.

In the water balance, authorized consumption is replaced by the effective use, which is divided into consumption for irrigation and consumption for other uses. The first one corresponds to the landscape water requirements (theoretical plants water needs), while the second regards other uses of water in the gardens (restaurants, fountains, lakes filling, etc). The water losses component includes a new subcomponent: the irrigation losses. This subcomponent comprises evaporation losses, deep percolation to the soil layers and runoff. Irrigation losses represent all the water that is consumed for irrigation but is not used to fulfil the plants water requirements.

In agreement with the water balance, the component of the energy balance regarding minimum energy is divided into two subcomponents: one for the minimum energy required for irrigation and one for the minimum energy required for the other uses.

Regarding the results from the application of the energy and the water balances in the three cases studies, the following conclusions can be drawn.

Firstly, the water balances allowed to estimate and to compare yearly water consumption in the case studies and to assess the importance of other water uses than irrigation. Also, the application of the water balance to consecutive years allowed assessing the effectiveness of implemented measures for water demand reduction. After the water balance is applied, further analysis of irrigation (or other uses) can be carried out to assess which areas (or activities) are the least efficient regarding water consumption and how to improve.

Secondly, the energy balance application allowed estimating yearly energy consumption in the gardens of Queluz and Vale do Lobo and the calculation of performance indicators. The energy balance of the historical gardens showed that the water distribution network of the gardens was adequately designed for an efficient use of the naturally available energy, allowing high water spurts but few energy waste. For Vale do Lobo gardens, the application of the energy balance allowed assessing the impact of water efficiency measures on energy efficiency. The energy efficiency performance indicators showed that the historical garden is much more efficient than the modern urban garden of Vale do Lobo.

7.2 Recommendations for future Works

With the conclusion of the present thesis, the following opportunities for further development of future work are identified:

- To further test the proposed water balance methodology in other gardens, including gardens with different water uses and sources.
- To test the proposed energy balance in gardens where water is supplied by local pumps and to assess energy efficiency improvement measures.
- To create a performance assessment system of both water and energy for urban gardens and to establish reference values for the indicators.

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