Assessment of water and energy efficiency in urban and historical gardens

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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January 2021

ACKNOWLEDGEMENTS

To my family that always encouraged me to do my very best even in moments I doubted myself, for all the conditions they provided me and wise words that were so important in this final step of my academic education.

To my supervisor Professor Dídia Covas, for all the help and support throughout this thesis, especially in the beginning when starting was more difficult for me and for the availability to help me.

To my other supervisor Doctor Laura Monteiro, who was as equally helpful, for all the follow-up, shared bibliography and for an enormous availability to improve my work and always clarify my doubts with the greatest possible support.

To Professor Ana Rodrigues for all the information provided and shared knowledge to me about the National Palace of Queluz and its gardens.

To Engineer Joana Carneiro, for all the help and time spent with me via Skype helping me with Autocad and other doubts I had along the way.

I would like to thank to Infralobo and Câmara Municipal de Cascais (CMC) for providing the data regarding Vale do Lobo garden and Marechal Carmona urban park. A special thanks to Mr. João Caetano from Infralobo and to Mr. Joaquim Gomes from Câmara Municipal de Cascais.

A special acknowledge is due to the Portuguese Science and Technology Foundation for funding of the project HORTO AQUAM SALUTAREM, PTDC/HAR-HIS/28627/2017 and associated research grant.

Last but not least, I would like to thank all my friends and special people in my life that were always by my side during my studies and social life. Without their support and motivation, the concretization of this thesis would be much harder.

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 systems) 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 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 studied 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 assessment of the effect of water and energy improvement measures.

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

Resumo

O consumo de água e energia em jardins urbanos ainda não foi extensivamente estudado, apesar de quantidades consideráveis de água e da associada energia serem consumidas nestas áreas verdes. A presente dissertação tem como objetivo o desenvolvimento e aplicação de uma metodologia para avaliação do consumo hídrico e energético em jardins urbanos e históricos. A metodologia é baseada em balanços hídricos e energéticos e indicadores de desempenhos associados, adaptados de balanços já existentes desenvolvidos para sistemas urbanos de abastecimento de água e sistemas hidroagrícolas. Os balanços propostos incluem novos componentes, tais como as necessidades de água do jardim, que são as necessidades de água teóricas das plantas. Estes balanços são aplicados a três casos de estudos de diferente natureza: os jardins do Palácio Nacional de Queluz (um jardim histórico), os jardins urbanos do Vale do Lobo (um jardim urbano com sistema de rega inteligente) e o parque urbano Marechal Carmona (um jardim com sistema de rega tradicional e usos recreativos). Os balanços hídricos permitem a estimativa e comparação anual da água consumida nos casos de estudo e avaliação da importância de outros usos da água para além da rega. A aplicação do balanço hídrico a anos consecutivos permite a avaliação da eficácia das medidas implementadas para a redução da procura de água. Os resultados mostram que os jardins históricos estudados consomem menos água do que os modernos e que a implementação de sistemas de rega inteligentes reduz efetivamente a quantidade de água consumida em jardins urbanos. A aplicação do balanço energético permite a avaliação do impacto de medidas de eficiência de água na eficiência da energia e demonstra que os jardins históricos são mais eficientes em termos de energia do que os modernos. A metodologia proposta pode ser aplicada em jardins com diferentes usos de água, para a avaliação do consumo de água e energia e para a identificação de medidas de melhoria no uso de água e energia.

Palavras-chave: jardins, balanço hídrico, balanço energético, uso eficiente da água, necessidades de água do jardim, perdas de água.

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ABBREVIATIONS

M – Irrigation meter

CU – Uniformity coefficient

DU – Distribution uniformity

ET – Evapotranspiration

IE – Irrigation efficiency

IPMA – Instituto Português do Mar e da Atmosfera

IWA – International Water Association

LoRaWAN – Long Range Area Network

LWR – Landscape water requirement

RRS – Relative rainfall supply

SIS – Smart irrigation system

WC – Real water consumption

SYMBOLS

Roman

A : area [m^2]

DU_{LQ} : lower quarter distribution uniformity (-)

e_a : actual vapour pressure [kPa]

e_s : saturation vapour pressure [kPa]

ET_L : landscape evapotranspiration [mm]

ET_0 : reference evapotranspiration [$mm.day^{-1}$]

g : gravity acceleration [$m.s^{-2}$]

G : soil heat flux density [$MJ.m^{-2}.day^{-1}$]

H : hydraulic head [m]

K_d : density factor (-)

K_L : landscape coefficient (-)

K_{mc} : microclimate factor (-)

K_s : species factor (-)

P : pressure [kPa]

Q : flow rate [l/s or m^3/h]

T : temperature [ºC]

R_a : allowable rainfall [mm]

R_n : net radiation at the crop surface [$MJ.m^{-2}.day^{-1}$]

U : mean velocity [$m.s^{-1}$]

Greek

Δ : slope vapor pressure curve [kPa/ºC]

γ : water specific weight [kPa/ºC]

1 INTRODUCTION

1.1 Context

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, 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). Water used to be looked at exclusively as a usable resource without considering the environmental consequences, but indeed water is a natural good necessary to the survival of all living beings.

Portugal does not have a severe water stress problem. Figure 1-1 shows that Portugal has an average volume of freshwater resources per inhabitant and per year of ca. 7 200 m^3 (Eurostat, 2017), but a country only undergoes water stress if the volume of water necessary per inhabitant is less than 1 700 m^3 (World Water Development, 2012). Nevertheless, Portugal suffers from the increased frequency and severity of droughts, which will directly affect water availability on the long term.

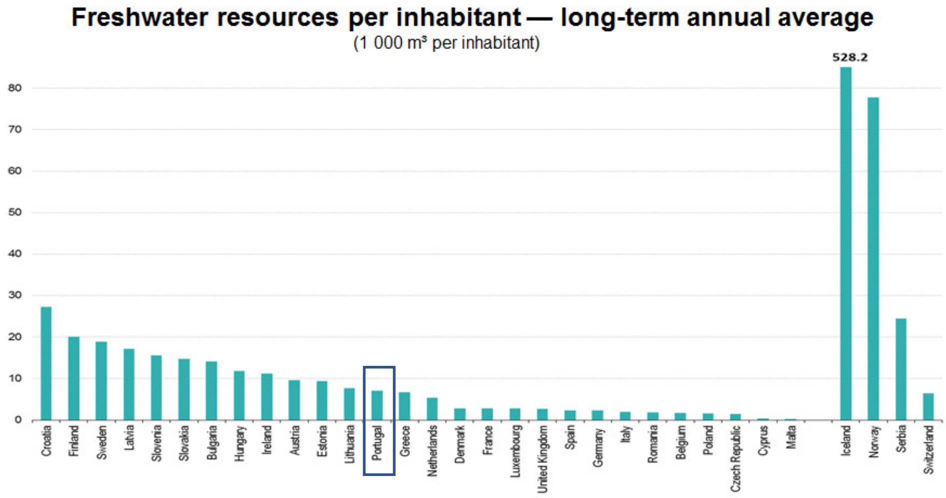


Figure 1-1 Freshwater resources per inhabitant in Europe (source: Eurostat database, 2017)

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 weight 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 garden areas that require a large amount of water.

1.2 Objectives and methodology

The main goal of this thesis is the development and application of a methodology to assess water and energy efficiency in all types of gardens, which include urban and historical gardens. The methodology is based on existing water and energy balances already developed for water supply systems and for irrigations systems. This methodology is applied and tested in three real case studies. The case studies include gardens of very different nature, with different uses of the water and distinct purposes, from the historical 18th century garden to the most modern garden with smart irrigation systems. These case studies were chosen to illustrate the wide application of the proposed balances in gardens with very different characteristics and specificities.

The thesis is composed of four main parts:

i) the literature review which includes the underlying concepts of the water and energy balances and the main approaches followed;

ii) the development of novel water and energy balances specific for irrigation systems of historical and urban gardens;

iii) the demonstration, testing and discussion of the proposed water and energy balances applied to three cases.

iv) establishment of recommendations for the application of the proposed balances to other garden irrigation systems.

1.3 Thesis Outline

The content presented in this thesis is divided into eight chapters; this introduction is part of the first chapter. Chapter 2 includes the state-of-the-art resulting in a resume of the principal concepts related with the dissertation. Chapter 3 presents the methodology for the water and energy balances calculation for gardens and other urban green areas. Chapters 4, 5 and 6 present the application of the methodology in three different case studies. The results are presented in detail and discussed accordingly. Chapter 7 presents a comparison of water and energy efficiency among the three case studies. Chapter 8 present the main conclusions and recommendations for future work. This thesis includes an appendix, with raw data that was used for the calculations and the generated data.

2 STATE-OF-THE-ART

2.1 Introduction

This chapter aims at presenting a literature review on existing approaches for assessing water-use and energy efficiency in different sectors, namely in the urban water sector (the water and energy balances) and in irrigation systems. This review will be of the utmost importance for establishing a homologous methodology for the modern urban gardens and green areas. This chapter also includes a description of water and energy consumption in both historical and modern urban gardens, factors affecting water use efficiency in gardens and water saving measures.

2.2 Water and energy consumption in gardens

2.2.1 Historical gardens

Since the old civilizations, gardens were created around the living human environment with the purpose of amazement by means of a pleasant aesthetics. Humans have always reshaped the environment in order to meet their goals, whether it is aesthetical or functional. The old Renaissance gardens and, later on, during the Baroque period, most gardens were created influenced by the water abundance. A large variety of fountains existed in these gardens and most water garden needs were, consequently, to allow water in the fountains and water for “shows”. Most of the plants species in these gardens required little or no water, that was mostly supplied by the rain (Babnik, 2012).

During the 17th century, there was a period of scientific evolution that marks the beginning of modern science (Cohen, 1994). In terms of water, in this specific period, the fundamentals of hydrostatics were established and, in general, a better understanding of the phenomena allowed the evolution of new and more powerful techniques capable to manipulate water, such as water pumps capable of elevating water from a lower altitude to a higher one. This new knowledge served to build magnificent water fountains in palaces and royal houses, such as the Palace of Versailles in France and the National Palace of Queluz, in Portugal, in which water was mostly used for aesthetic purposes (Correia, 2015). In this context, by means of fountains with water spurts (Figure 2-1) and other components, such as cascades that illustrated the water abundance, hardly any water was used for irrigation purposes. In terms of energy use, the systems used in historical gardens were mainly gravitational, using only the natural energy available from the slope of the underlying terrains.

The existence of upper reservoirs or storage tanks, located at a higher elevation, is a typical characteristic of the hydraulic systems in gardens and it denotes the influence of the Roman hydraulic tradition in the Iberian Peninsula (Marín, 2020). Tradition that was strongly influenced by the Islamic culture presence in the Iberian Peninsula, mainly the concept of a gravitational water system (Glick, 2005; Rodrigues, 2020; Rodrigues and Romero, 2020). The reservoirs and tanks allowed to store water and, most importantly, allowed the water to flow by gravity to the downstream supply systems. In addition, in many gardens, water tanks also served as water mirrors, providing great aesthetic value (Rodrigues and Marín, 2020). This feature is found in many hydraulic systems of gardens, similar to the one of the National Palace of Queluz, in which water plays a major role for the gardens aesthetics and irrigation, like Aranjuez, Casa de Campo, Valsaín, El Escorial, La fresneda and El Bosque de Béjar

(Marín, 2020). These water supply systems shaped the way gardens and palaces were spatially organized, depending on the water transportation infrastructures that better fitted the topography of the sites. Available water was (and still is) scarce in arid areas, like the Iberian Peninsula, in comparison to the high water demand of the gardens and, thus, all water sources located nearby the garden location (i.e., rivers, streams and underground sources) had to be explored.

This typical hydraulic system layout guaranteed enough pressure to allow the water “shows” at the several fountains and the operation of irrigation systems. In this sense, it was not the royal properties and their gardens that influenced the hydraulic constructions, but the other way around. Gravity was the main force and gravity based systems were unavoidable to make the water supply possible. For this reason, each site was carefully chosen in terms of water availability (whether rivers, streams or other underground sources) and terrain topography (sloppy terrains were preferred to allow gravity fed water systems). Additionally, the first pumps used in the past did not use electrical energy and most of the equipment used to extract water from underground sources came from pumps powered by human or animal forces (Yannopoulos et al., 2015). Figure 2-1 below illustrates an example of an historical garden layout and its typical components.

Figure 2-1 National Queluz palace historical garden.

2.2.2 Modern urban gardens

Modern urban gardens and nowadays green areas architecture is quite different from that of the 18th century. Today’s urban gardens have more areas with turfgrass (Figure 2-2) and plants that require irrigation for its maintenance and aesthetics. Consequently, more water is needed when compared with historical gardens. It is very common to have gardens with large green areas (i.e., turfgrass and shrubs where irrigation is mandatory to allow a fresh and green environment), that is the normal picture associated to modern urban gardens.

In today’s modern urban gardens, not only water is needed for irrigation, but also the majority of these gardens are used also for recreational activities and leisure. Consequently, there are water uses related with drinking fountains existing in the gardens, as well as small cafés, toilets and restaurants. Water use is not strictly for irrigation. This is a major difference when comparing the today’s gardens architecture with past gardens architecture (Figure 2-1 versus Figure 2-2) which directly impacts different types of water consumption. Water is commonly consumed today to guarantee the functioning of the park, such as irrigation, bringing water to the cafés or toilets, whereas water consumption in the past gardens served more as a "piece" of aesthetics that was well present at the eyes of the people crossing the gardens. Today it is not common to see a fountain with water spurts in the urban gardens.

Figure 2-2 Examples of a modern urban garden.

In terms of energy use, nowadays, in modern urban gardens, there are sophisticated irrigation systems, the majority of them being automated, which require a considerable amount of energy, mostly electrical, contrary to ancient irrigation techniques free of electrical energy use. The major difference between automated irrigation and ancient irrigations techniques is that nowadays irrigation includes components which need electrical energy and, thus, modern urban gardens are more energy intensive in this sense. Irrigations systems continue to evolve over time and some of them can be denominated as "smart systems", with the purpose of turning irrigation systems as more efficient as possible and automated, irrigating according to plants water requirements (Jamuna et al., 2020). This type of irrigation makes use of sensors that allow to check when soil moisture is bellow a defined level, meteorological stations that measure temperature, precipitation, humidity, evapotranspiration and other indicators and plant-care databases to irrigate only when needed and the exact amount of water needed. All of these new elements require electrical energy for functioning (Caetano et al., 2014).

Irrigation systems of the gardens are generally connected to the public water supply network, consequently avail the network pressure for their functioning. Other systems have underground water sources and to extract the water need to spend energy for the functioning of the pumps.

Concluding, today's energy and water use in modern urban gardens or green areas is different, mainly due to the characteristics of these areas. Before water use was mostly for aesthetic purposes, using water to fill fountains and produce water shows and today the water is mostly used for irrigation to maintain a green healthy environment for the plants existent in the garden and to guarantee other uses functioning. In terms of energy, there was a major shift from the past non-automated irrigation systems to today's smart and energy intensive use irrigation systems.

2.3 Factors affecting water use efficiency in gardens

The irrigation of modern urban gardens is one of the most significant water demand activities in urban areas. In order for the irrigation to be more efficient as possible, the right irrigation method should be applied for each area: sprinkler irrigation or microirrigation. The amount of water needed depends also on the type of plants in the gardens.

2.3.1 Plants water requirements

Each plant species has different water needs. Tables 2-1 and 2-2 show a comparison of water needs for trees, shrubs and groundcovers and compares both drought and non-drought tolerant species (Zureikat et al., 2012).

Table 2-1 Trees and shrubs water requirements.

Trees & Shrubs	**Water Requirements (L\ Tree for 6-month dry season)**
Non-drought-tolerant trees	1200
Drought-tolerant trees	360
Native trees	0
Non-drought-tolerant shrubs	960
Drought-tolerant shrubs	540

Table 2-2 Groundcovers water requirements.

Groundcovers	**Water Requirements (L\m^3 for 6-month dry season)**
Lawn or Dichondra	1680
Non-drought-tolerant groundcovers	1080
Drought-tolerant groundcovers	360

The planted species have a great influence on the use of water in the green areas. Some species require more water to survive, whereas others can subsist with few water. Autochthones species (native) or others adapted to local climatic conditions are generally those that require less irrigation. From the diverse types of vegetation existing in urban green areas, turfgrass is the one that requires the most water to remain green and to fulfil the aesthetics objective of its choice. Furthermore, developed trees, due to their deeper roots, have access to greater water storage in the soil, requiring less irrigation. Additionally, the trees shade the plants around them, reducing the evapotranspiration of the green area, contributing to the reduction of water consumption for irrigation.

Evapotranspiration

Water needs of a certain specie corresponds to the evapotranspiration, ET, of that specie in a given environment. The evapotranspiration of a plant species is the sum of transpiration of plants and the evaporation of water in the soil, both occurring at the same time, Figure 2-3 (Santos Pereira, 2004).

Evapotranspiration depends on the climatic conditions, increasing with incident solar radiation, but also varies with plant growth, the fraction of solar radiation reaching the soil is higher when the plant is in its early stages due to reduced shading, which will result in higher ET (G. Allen et al., 1990).

Evapotranspiration depends on climate and weather parameters, management of the site and depends on each specie characteristics (Khangaonkar et al., 1991).

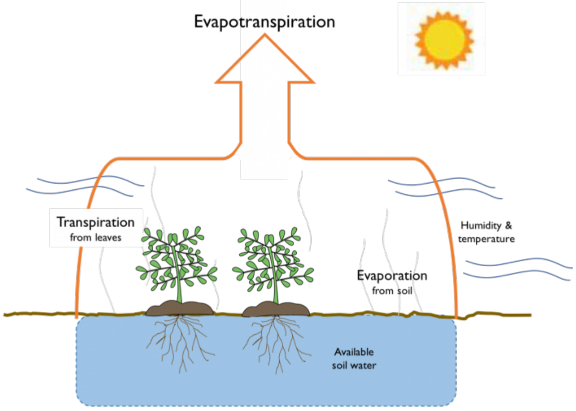


Figure 2-3 Evapotranspiration representation adapted from Bates (1980).

The reference evapotranspiration, ET_0, corresponds to a reference surface, active growing grass surface with a height of 0.12 m, fixed surface resistance of 70 s/m and an albedo of 0.23, covering totally the soil and without water stress (Khangaonkar et al., 1991). This concept of a reference evapotranspiration was introduced to study the evaporative demand of atmosphere independently of the type of culture and its management. The only factors that influence this parameter are climatic parameters, since it does not attend to culture characteristics or type of soil, (Rodrigues & Pereira, 2008).

The method Penman-Monteith adopted by FAO (Allen et al., 1998) (Equation 1) is recommended to obtain ET_0. It approximates ET_0 of grass to the evaluated site, implying physiological and aerodynamic parameters of the culture, as follows:

$$ET_0 = \frac{0{,}408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0{,}34 U_2)} \tag{1}$$

where ET_0 is the reference evapotranspiration [mm.day^{-1}], R_n is the net radiation at the crop surface [MJ.m^{-2}.day^{-1}], G is the soil heat flux density [MJ.m^{-2}.day^{-1}], T is the mean daily air temperature at 2 m height [ºC], U_2 is the wind speed at 2 m height [m.s^{-1}], e_s is the saturation vapour pressure [kPa], e_a is the actual vapour pressure [kPa], e_s is the saturation vapour pressure deficit [kPa], Δ is the slope of the vapour pressure curve variation with temperature [kPa/ºC] and γ is the psychrometric constant [kPa/ºC].

It is very difficult to obtain a certain species evapotranspiration, ET_s, as several climatic parameters and evaporation surface characteristics must be known. The aim of obtaining a reference evapotranspiration, ET_0, is to later allow the calculation of ET_s multiplying ET_0 by a species coefficient, K_s (Santos Pereira, 2004):

$$ET_s = ET_0 . K_s \tag{2}$$

The species coefficient, K_s, used to estimate ET_S and to estimate evapotranspiration of each species (Allen et al., 1998) can be found in literature (Costello et al., 2000).

Landscape water requirements

Normally an urban green area is composed of several plants species with different water needs. The calculation of ET_s for each specie is very time consuming. To overcome this situation, the green area is typically divided in hydro zones (i.e., zones where the cultures have similar water needs, similar densities and subjected to the same climatic conditions) and the evapotranspiration of the land, ET_L, in gardens is calculated by using a landscape coefficient, K_L, for each of these zones (Irrigation Association and the American Society of Irrigation Consultants, 2014).

The coefficient K_L is similar to K_s with the difference that it aggregates several different plant species of the same zone. The calculation of K_L requires taking into account the species effect, density and microclimate, as follows (Costello et al., 2000).

$$\mathrm{K_L = K_s . K_d . K_{mc}} \tag{3}$$

where K_L is the landscape coefficient, K_s is the species factor, K_d is the density factor, K_{mc} is the microclimate factor. There is not a K_s standard table available for each plant species. The choice of the K_s value must come from the gardening professional knowledge of local climate and garden conditions. The value of K_s can be chosen according to existing different species in the garden and an average must be done. The value of K_d depends on the density of the garden, ranging from 0.5-1.3, being higher values related with denser areas. Gardens density is also related with gardens age: older gardens are more commonly considered to be denser since the vegetation is more mature. It needs to be considered the type of vegetation in order to obtain this coefficient. Parameter K_{mc} represents microclimate coefficient; for instance, if the garden is located in the shades of a building, it accounts for the factors that influence the normal climate of the surrounding area of the garden (Costello et al., 2000).

The evapotranspiration of the land, ET_L, can be estimated by multiplying the reference evapotranspiration by the coefficient K_L:

$$\mathrm{ET_L = ET_0 . K_L} \tag{4}$$

2.3.2 Irrigation systems layout and equipment

The installed irrigation technologies and the irrigation system condition play also a key role in the efficiency of water use in green areas. The irrigation technologies that direct water to the plants root are, generally, more efficient than those that promote the water spreading. The existence of leakage in these systems, that typically operate under pressure, is inevitable. However, leaks can, and should be minimized, whether by the correct preventive maintenance of the systems, substituting of obsolete equipment or by the immediate detection and repair of detected ruptures. Also, the number of sprinklers, the spacing between them and their direction are characteristics of the system that influence irrigation efficiency, because they will directly affect the uniform distribution of the water in the irrigating area. The operational pressure of the systems is also an important factor, since very high pressures contribute to the frequency and intensity of the ruptures.

The irrigation system is composed of several components (Figure 2-4). The most important ones are the main and secondary pipes, the flowmeter, the backflow valve, the control valves and the sprinkler nozzles and or/drippers (Moore et. al, 2019). It is very important the design stage of these components in an irrigation system, because it will have a direct influence on systems' pressure. Each irrigation system component has the optimal operating pressure with an operating range allowed to achieve the highest efficiency.

The flowmeter is used to measure the volume of water that is used in an irrigation system in a certain zone. The number of flowmeters depend on the area of the garden. Ideally, the gardens are divided in zones and each zone should have a flowmeter. This is an important component to keep record of the water volume that enters into the system.

Control valves are used to turn a sprinkler system on or off, allowing the flow of a certain volume of water. Currently, electrovalves are the most common. They are controlled via a controller which sends an electrical signal to open or to close the electrovalve (automatic operation). Controllers commonly control more than one valve. Each control valve is responsible for controlling the flow of water in one irrigation zone. Gardens with a larger area are normally divided into zones, each zone having their own control valve. The main pipes correspond to the principal pipes that connect the water source to the irrigation zone control valves. The main pipe in the irrigation system is usually filled with water and pressurized. It should be regularly checked, because a leakage in this pipe will waste a large amount of water. The secondary pipes correspond to the set of distribution pipes that will transport the water from the control valves to the final destination, sprinklers or drippers. These pipes may be smaller in terms of diameter. Secondary pipes are usually more (main pipe subdivides into several secondary pipes) depending on the size of the garden. Depending on the type of irrigation system, used sprinklers or drippers are used to deliver water to the plants, it can be used both in a garden with both types of irrigation methods divided into zones.

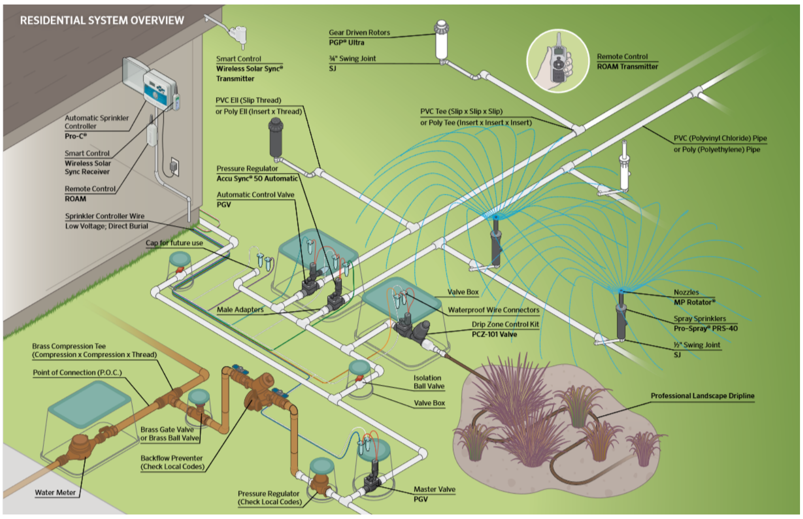


Figure 2-4 Typical components in an irrigation system (Moore et. al, 2019).

Irrigation in the urban gardens can be carried out by means of different irrigation methods. The selection of the irrigation method to apply to the gardens depends on their characteristics. If there are wide spaces with turfgrass, it needs to be applied an irrigation method of long range (i.e., sprinkler irrigation). If there are areas with flowerbeds in the garden, a more localized irrigation method should be used (i.e. microirrigation).

Sprinkler irrigation

Nowadays, sprinkler irrigation is a very common method, where several sprinklers are spread on the site, especially used in turfgrass areas.

For an efficient irrigation, it is important to respect soil infiltration rate, uniformly irrigating the site guaranteeing sprinkler pluviometry is lower than infiltration rate, avoiding water runoff and cultures damaging. In slope irrigation sites, infiltration is even lower and water runoff is ever faster, so, in these cases, irrigation flowrate should be lower than the soil infiltration rate (Santos Pereira, 2004).

Sprinklers and the nozzles are two indispensable components for sprinkler irrigation systems. They are responsible for distributing the water over the land as uniformly as possible, guaranteeing effectiveness and efficiency of the irrigation system. There are different types of sprinkler technologies. Multiple nozzle arrangement is the most efficient technology because water is irrigated at different distances along the radios coverage of the sprinklers, allowing for a higher water application uniformity (CAST, 2008).

Sprinkler irrigation equipment flexibility and efficiency make their applicability almost universal, for the majority of climatic and topographic conditions. However, temperature and wind velocity associated with low humidity result in high water losses due to evaporation, being this the main disadvantage related with sprinkler irrigation. Another disadvantage is that sprinklers do not adapt to low soil infiltration rate.

Microirrigation

Microirrigation, also called localized irrigation, is a method in which small quantities of water are supplied to the root of the plants. The application of water in micro-irrigation requires a network of main and secondary pipes normally arranged on the ground. The equipment used to apply water to the soil and the root of the culture is called emitters. There is a similarity between sprinkler irrigation and microirrigation, as both of these methods irrigate under pressure using a pipe system and emitters that are regularly spaced on the site. The difference is that, in microirrigation, the water pressure and flow rate are much lower, resulting in smaller water application and lower time interval between irrigations comparatively with sprinkler irrigation (Santos Pereira & Trout, 1999).

Microirrigation is specially adequate to supply small water quantities with high frequency, that will allow to maintain soil good conditions and avoid water stress. The main advantage of this system is water savings, providing the plants with the amount of water needed, as minimum as possible, avoiding water runoff (Santos Pereira, 2004). Another relevant advantage is the possibility to irrigate in almost all types of topographies. Figure 2-5 bellow shows an example of microirrigation and another of sprinkler irrigation.

Figure 2-5 Microirrigation (on the left) and sprinkler irrigation (on the right) in public urban gardens.

Not all soils are indicated for microirrigation. Sandy soils are not fit for microirrigation, for example, because water in this coarser type of soil will more easily and faster percolate deeply (CAST, 2008). So, in the case of a sandy soil, micro sprinkler or drip irrigation with more emitters should be chosen that will irrigate more frequently but with lower water quantity. Opposite, finer-textured soils are more adequate for this irrigation method, but the emitters should be further apart (Santos Pereira, 2004).

Santos Pereira (2004) also referred other disadvantages associated with this method, such as higher equipment costs when compared with sprinkler irrigation and the emitter holes easier get obstructions by small mineral particles or organic matter which affects uniformity of water distribution and reduces flow.

2.3.3 Irrigation practices

Irrigation practices carried out in urban green areas also play a decisive role in the water efficient use. Adjusting irrigation volumes and times to the actual needs of the plants, given the local climatic conditions, is essential to avoid waste. Scheduled irrigation is generally more efficient than manual irrigation and it should be scheduled to operate preferably at night, when evaporation is lower, allowing the maintenance of soil moisture levels.

The modern automatic irrigation systems have a high degree of automation that rely on electrical equipment able to automatically decide when and if irrigation is needed, thus reducing water waste. These include modern controllers that schedule irrigation times based on the current climatic and soil conditions; they use hourly information of local climate and adapt the irrigation schedule according to plant water needs (WaterSense, 2017). They are able to know the exact immediate local climatic conditions because they are connected to meteorological stations that monitor the solar radiation, pluviometry, wind velocity and direction, temperature and humidity. Figure 2-6 shows an example of an irrigation controller by WaterSense.

Figure 2-6 Irrigation controller by WaterSense.

Typically, opting for these type of controller when comparing with the traditional ones coupled with a clock and a fixed schedule will allow less water losses (WaterSense, 2017).

Modern controllers are not only able to manage irrigation schedules but are also able to detect defaults in the electrovalves, detect leakages in the pipe network, issue reports about the overall system and quantify water consumption (Manso et al., 2019).

Other components of the modern irrigation systems, besides the controllers, are the electrovalves mentioned above which open or close, induced by an electrical signal that comes from the controller, indicating irrigation must start or stop. One controller is able to control more than one electrovalves. Other components are the sensors that monitor different parameters, such as, soil moisture or climatic variables and telemetry; these sensors allows for the measurement and communication between systems via wireless communication devices.

Figure 2-7 depicts an example of a modern smart irrigation system, in which water consumption, irrigation and the urban park functioning is carefully controlled and remotely operated. The environmental indicators and the water consumptions are monitored, thus allowing a smart irrigation programming. This figure shows how the use of these type of technology is able to better manage water consumption in an urban garden.

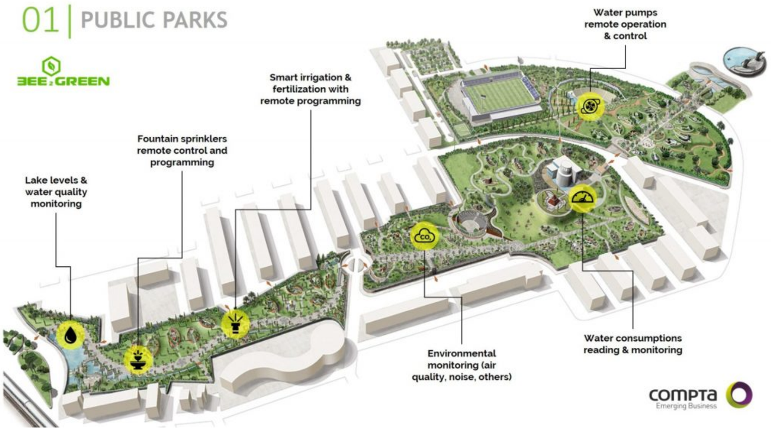


Figure 2-7 Example of a modern urban park using remote technology (source: COMPTA Emerging Business).

2.4 Water saving measures in gardens

Several aspects influence water use in a garden. The used irrigation method is often not the most adequate. Each plant species has different water needs and requires different irrigation methods. It needs to be further studied the water needs and the most adequate irrigation method, with the highest efficiency, to better design an irrigation plan that saves as much energy and water as possible (WaterSense, 2017).

According to CAST (2008), the following factors should be taken into account when designing an irrigation system: avoid high water consumption plants, avoid decreased irrigated landscape areas, reduce the quantity of grass in a garden, chose smaller large trees/plants and low plants density; and maintain healthy soils, allowing the plants to develop a strong deep root zone.

Functional landscapes should be chosen to avoid excessive water use. Considering previous factors can be the starting point to achieve a water-smart landscape; any irrigation system project needs to first look into these steps and try as much as possible to decrease water use.

The site preparation and planning is an important step. Native vegetation and soils should be chosen because they require less irrigation besides water provided from the rainfall. It should be avoided garden construction in slope landscapes to reduce water runoff and, before the landscape is installed, it should be ensured that the soil is properly amended, tilled and contoured to hold water. Both the plant species and the correct maintenance of the soil are important factors, when it comes to reducing water waste. In terms of plant selection, as mentioned in section 2.3.1, there are different plants water needs and so it should be chosen for the urban gardens the species that will thrive in each particular area, with specific local climate conditions. Incorporating plants near large shade trees is another measure that will reduce evapotranspiration of the plants, requiring less irrigation. Practice hydro zoning (grouping plants with similar water requirements) should be incorporated in the landscape, allowing the volume of water used for during irrigation will be the most adequate for each zone.

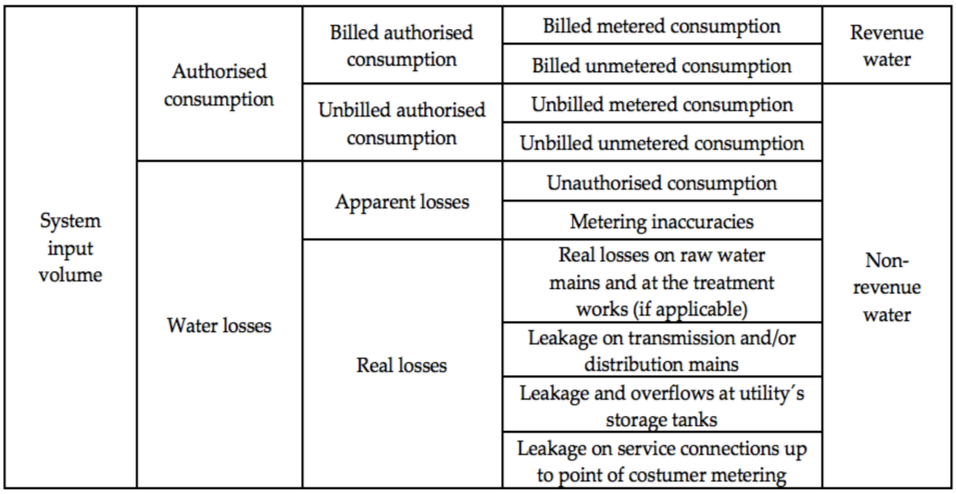
2.5 Water-use and energy efficiency assessment approaches

2.5.1 The water balance

In order to access water supply systems efficiency, it is important to quantify water that comes in and out of the system. The difference between these two represents water losses, which is an important indicator of efficiency. The water loss should be the least as possible, due to economic, environmental and sustainability reasons (Lambert and Hirner, 2000).

Water Balance for urban water supply systems

International Water Association (IWA) proposed, in 2000, a water balance for urban water supply systems scheme (Lambert and Hirner, 2000) with the purpose to identify the water paths in all the system integrity, quantifying water losses and allowing to understand where the main problems in the system are. Normally, water balances are built for one year and efficiency measures are proposed. From one year to another, water balances should be compared to check if the applied measures are making a difference in terms of increasing efficiency. A more complete scheme was developed by Alegre *et al.* (2006), able to be applied in more systems, including more stages from water abstraction to distribution. The most recent version of the water balance (Alegre et al., 2016) is presented in Figure 2-8. In this version, metering inaccuracies and real losses on raw water mains and at the treatment works were added.



System input volume	Authorised consumption	Billed authorised consumption	Billed metered consumption	Revenue water
			Billed unmetered consumption	
		Unbilled authorised consumption	Unbilled metered consumption	Non-revenue water
			Unbilled unmetered consumption	
	Water losses	Apparent losses	Unauthorised consumption	
			Metering inaccuracies	
		Real losses	Real losses on raw water mains and at the treatment works (if applicable)	
			Leakage on transmission and/or distribution mains	
			Leakage and overflows at utility´s storage tanks	
			Leakage on service connections up to point of costumer metering	

Figure 2-8 Water balance proposed by Alegre et al. (2016) for urban water supply systems, in m^3/year.

Building these water balances schemes allows to calculate revenue water, a commonly used metrics to calculate system efficiency. The calculation of the balance starts with the estimation of the water that comes into the system (system input volume), followed by the assessment of authorized consumption. Water losses result from the difference between system input volume and authorized consumption, apparent losses are, afterwards, estimated and, finally, real losses are estimated.

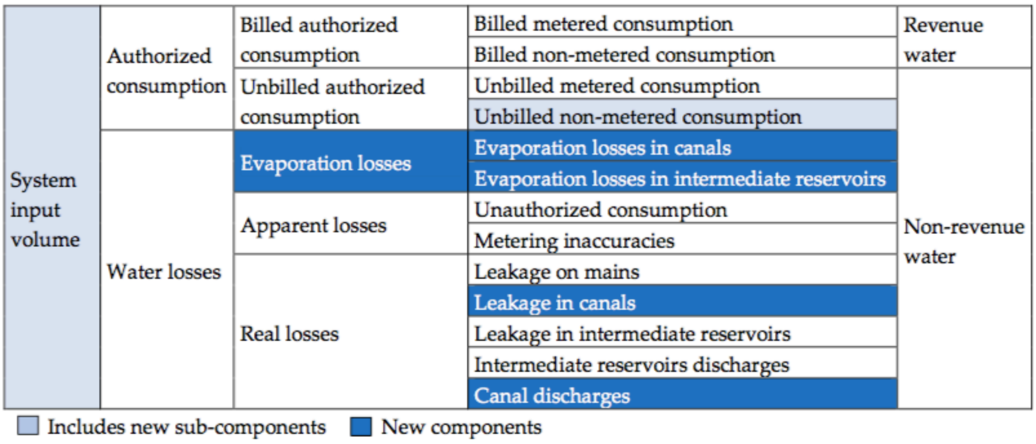
System input volume is the first component to be calculated. It corresponds to the total volume introduced into the water supply system, during the reference period (Alegre et al., 2006). It needs to be included here all sources of water that correspond to the total water input in the system (rivers, furrows, dams or water imported from other systems) (Cunha, 2018). Water balance calculation needs water volume estimations, it should be used calibrated meters for that purpose, if those are not available, estimates must be done based on available data or application of other reliable engineering techniques (Alegre et al., 2006). System input volume is divided between authorised consumption and water losses. Authorised consumption should quantify billed or unbilled, metered or unmetered consumption.

Authorised consumption corresponds to the total water volume supplied to authorized consumers, namely the water utility itself and domestics, commercial and industrial consumers, during the reference period; it includes exported water. Billed metered consumption results from readings of the measurement devices installed at the water delivery points of the consumers. Billed unmetered consumption represents the volume of water that is delivered to the consumers but it is not measured because the consumer does not have a measurement device installed; management entity must estimate these water volumes as best as possible. Unbilled authorised consumption includes all the water volume the water utility allows to be consumed without billing (i.e., authorised volumes for pipes cleaning, street cleaning, public gardens irrigation). Unbilled metered consumption is obtained the same way as billed metered consumption but, in this case, it is not billed (Alegre et al., 2006).

The **water losses** correspond to the difference between system input volume and authorised consumption. Water losses may be considered for all the system or calculated for a certain subsystem (i.e. distribution system). Water losses are divided between apparent and real losses (Alegre et al., 2006). Apparent losses are the first to be calculated, since, in most of the cases, correspond to consumed water volumes that were not measured or registered; these losses account for all types of inaccuracies associated with water measurements and also unauthorised consumption (illicit use). Real losses account for all the physical water losses of the pressurised system (ruptures, leakages, overflow) from the moment water enters into the system until it reaches the user meter.

Water balance for collective irrigation systems

Based on the water balance proposed by Alegre at al. (2016), it was developed a water balance for collective irrigation systems by Cunha (2018) presented in Figure 2-9. This water balance, with some differences and adaptations to the water balance proposed by IWA in 2000, will serve as a starting point to build a water balance for irrigation systems in urban sites.



System input volume	Authorized consumption	Billed authorized consumption	Billed metered consumption	Revenue water
			Billed non-metered consumption	
		Unbilled authorized consumption	Unbilled metered consumption	Non-revenue water
			Unbilled non-metered consumption	
	Water losses	Evaporation losses	Evaporation losses in canals	
			Evaporation losses in intermediate reservoirs	
		Apparent losses	Unauthorized consumption	
			Metering inaccuracies	
		Real losses	Leakage on mains	
			Leakage in canals	
			Leakage in intermediate reservoirs	
			Intermediate reservoirs discharges	
			Canal discharges	

▢ Includes new sub-components ■ New components

Figure 2-9 Proposed water balance for collective irrigation systems in m^3 (Cunha, 2018).

In this water balance adapted version, evaporation losses are added as a subcomponent of water losses, since most of the irrigation in agriculture is carried out via open canals which suffer considerable water losses by evaporation. Subcomponents were also added to the real losses component, such as leakages in canals and canal discharges, which need to be accounted for in the agriculture context.

2.5.2 The energy balance

The energy balance is directly related with the water balance, since it quantifies the amount of water related energy that enters and exits the pipe system. The construction of a complete water balance will allow to identify energy consumption of a system, thus will allow to identify the system components that require improvement in terms of energy efficiency (Mamade et al., 2018).

It is very important to build a complete water balance because the energy balance scheme will be built based on water balances components, such as system input volume and authorized consumption. The apparent losses are not usually taken into account in energy efficiency studies. Despite that, a reduction of unauthorized consumption and metering inaccuracies in the water balance will lead to the decrease in energy use and so higher energy efficiency. When it comes to real losses, the decrease in water losses due to leaks and ruptures in transmission and distribution pipes has a strong impact in energy use (Mamade, 2019).

Energy can be dissipated due to water losses, friction losses, inadequate operating practices or inadequate network layout. The energy balances aims to identify where the main energy inefficiencies are in the supply or distribution system (Mamade et al., 2014).

Energy balance considers the energy supplied to the system by gravity and by pumping, the minimum required energy to guarantee consumption, the dissipated energy in valves, pumps and pipes and the surplus energy. This balance also allows the estimation of dissipated energy due to water losses (Mamade et al., 2017). Energy balances allows for the water utilities to analyze the effects of the measures implemented in terms of energy consumption.

Energy balance for urban water supply systems

Figure 2-10 shows the components of the energy balance proposed by Mamade (2019) for urban water supply systems. The reference period in the energy balance must be the same as in the water balance, because the volumes used in the water balance will serve as the basis for the energy balance volumes.

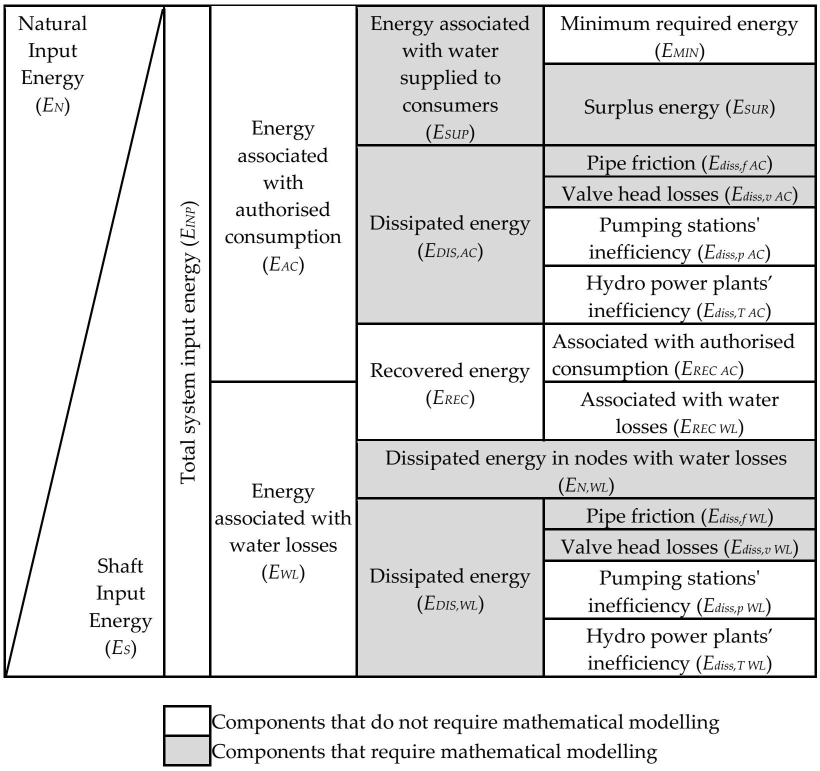


Figure 2-10 Components of energy balance (kWh) proposed by Mamade (2019).

The proposed balance by Mamade, (2019) has two approaches for the energy balance calculation: top-down and bottom-up approach.

The top-down approach does not require hydraulic modelling of the systems network, using the information of the water balance to obtain energy associated with authorized consumption and energy associated with water losses. This approach has the advantage of directly assessing the effects on energy efficiency by reducing water losses. This approach allows the calculation of several components except those represented in grey in Figure 2-10. This method allows to have a global overview of the components that consume energy in a simple way and not requiring an hydraulic model to calculate energy balance.

The bottom-up approach (detailed energy balance) requires a calibrated hydraulic model and allows the calculation of all energy balance components. This approach is more difficult to apply because most utilities do not have their networks modelled and more data is needed in order to successfully obtain the detailed balance. The commonly software to run the hydraulic simulations is EPANET.

Energy balance for collective irrigation systems

An energy balance specific for collective irrigation systems composed of open channel canals and pressurized pipes was developed by Cunha (2018), depicted in Figure 2-11. This balance was developed based on the energy balance for urban supply systems and was applied the top-down approach for specific case studies.

<table>
<tr><td rowspan="10">Energy supplied to the system</td><td rowspan="7">Energy associated with authorized consumption</td><td rowspan="2">Energy supplied to consumers</td><td>Minimum required energy</td></tr>
<tr><td>Surplus energy</td></tr>
<tr><td rowspan="4">Dissipated energy associated with consumption</td><td>... in canals and mains (*)</td></tr>
<tr><td>... In floodgates and valves (*)</td></tr>
<tr><td>... In pumps</td></tr>
<tr><td>... In turbines</td></tr>
<tr><td rowspan="2">Recovered energy</td><td>... associated with consumption</td></tr>
<tr><td rowspan="6">Energy associated with water losses</td><td>... associated with losses</td></tr>
<tr><td rowspan="5">Dissipated energy associated with loses</td><td>... where losses occur (*)</td></tr>
<tr><td>... in canals and mains (*)</td></tr>
<tr><td rowspan="3">Energy associated with the contribution of the intermediate reservoirs</td><td>... in floodgates and valves (*)</td></tr>
<tr><td>... in pumps</td></tr>
<tr><td>... in turbines</td></tr>
</table>

(*) very distinct components of the urban systems

Figure 2-11 Energy balance of collective irrigation systems (kWh) proposed by Cunha (2018).

2.6 Motivation and lacks of knowledge

Water consumption in urban gardens is very high, being irrigation one of the water uses that consumes a considerable amount of water in gardens. Irrigation can be carried out more efficiently, since water in excess is, often, given to the cultures. Moreover, the irrigation system is typically pressurized, even when it is not irrigating, water is lost in existing leaks and ruptures. Currently, there is a lack of knowledge on the amount of water that is actually lost due to excessive irrigation and leakage.

Ancient water supply systems of historical gardens demanded less water volumes and energy (gravitational water and energy supply) in comparison to modern urban gardens. Thus, it would be interesting to inspire today's garden systems in older and less consuming historical systems, trying to implement today practices applied centuries ago.

Despite existing water and energy balances for urban systems and for collective irrigation systems, there is a lack of water and energy balances specific for the irrigation systems of gardens, resulting in an extra motivation for the development of this thesis. It was only found one study focusing on the water balance calculation for city gardens (Ruíz-Pérez et al., 2020) in which a different water balance was developed, with some similarities to the water balance proposed in this thesis.

3 METHODOLOGY

3.1 Introduction

A novel methodology to assess water and energy consumption in gardens and urban green areas is proposed. The methodology is based on the calculation of water and energy balances. Novel water and energy balances, based on those proposed for water supply and collective irrigation systems, are developed for the specificities of urban gardens and green areas, including new components and subcomponents, as described in the following sections.

3.2 Water balance

3.2.1 Water balance structure

A novel water balance for assessing water consumption in gardens and urban green areas is developed (Figure 3-1), 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 3-1 Components of the water balance for gardens (in m^3/year).

The physical boundaries of the system to be analysed should be established and the reference period should be defined. The system should contain the infrastructures and equipment that ensure the service. The reference period should coincide with the working period of the system. In this specific case the working period is related with the irrigation months, which normally occur during the summer season, but it may also be necessary to irrigate during winter season, if that year is atypically dry or if there is a need to establish the turfgrass conditions (i.e., in case of an event happening during the winter that might disturb the turfgrass). Thus, it is recommended that the reference period is of one year.

3.2.2 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. Figure 3-2 resumes the system input volume subcomponents.

System input volume

- Network supply
- Underground sources
- Reclaimed water or harvested rainwater

Figure 3-2 Subcomponents of the system input volume.

3.2.3 Effective use

Effective water use is the second component of the balance to be calculated. This is divided in 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):

$$LWR = \frac{1}{DU_{LQ}}(ET_0.K_L - R_a)A \qquad (5)$$

where LWR is the landscape water requirement [m^3/month], 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. Both can be found in the literature (USEPA, 2009). The reference values for evapotranspiration and precipitation can be taken from the nearest meteorological station of the garden and can be daily or monthly, depending if the LWR is preferred to be 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 not irrigation, discounting the water losses. In some systems the consumption for other uses is zero, as for example in case study described in Chapter 5, in which water is only used for irrigation and there are no other water uses. Figure 3-3 summarizes effective use subcomponents.

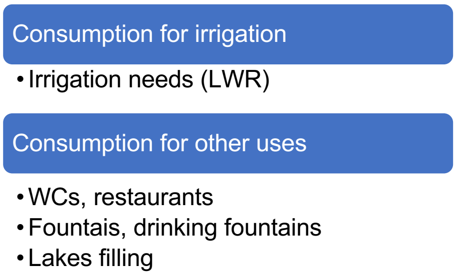


Figure 3-3 Sub components of the effective use.

3.2.4 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 balance 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.

Figure 3-4 summarizes the subcomponents of water losses.

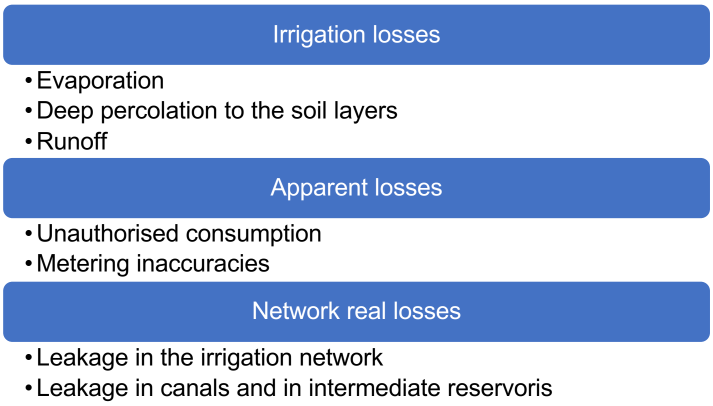


Figure 3-4 Sub components of water losses.

3.3 Energy balance

3.3.1 Energy balance structure

An energy balance specific for gardens and urban green areas is developed (Figure 3-5), 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.

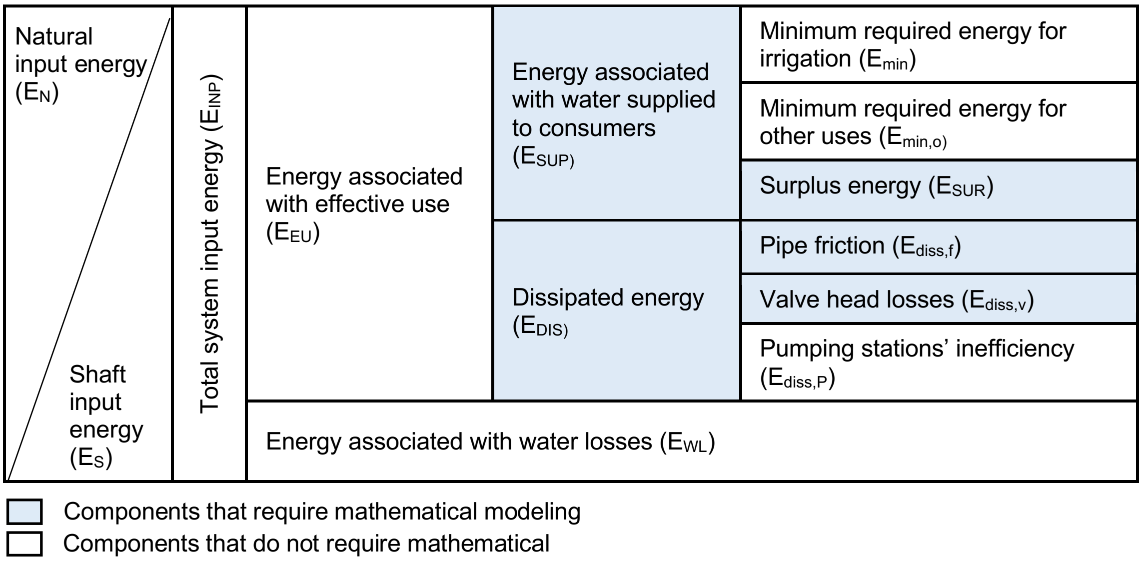


Figure 3-5 Proposed energy balance in gardens and urban green areas (kWh)

3.3.2 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 entrance of the system. In most irrigation systems natural input energy is referred only as pressurized energy delivered at the systems entrance. Shaft input energy, E_S, is associated with energy supplied by all the pumping stations. 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:

$$E_{INP} = \frac{\gamma\ V_{consumed}\ H_{app}}{3600*1000} \tag{6}$$

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 applied in the irrigation system [m]. The pressure head can be obtained as follows:

$$H_{app} = Z_e + \frac{P_{inlet}}{\gamma} - Z_0 \tag{7}$$

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].

3.3.3 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:

$$E_{min} = \frac{\sum_{i=0}^{n} \gamma\ V_{theoretical,i}\ Hmin_i}{3600*1000} \tag{8}$$

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:

$$H_{min,i} = Z_i + \frac{P_{min}}{\gamma} - Z_0 \tag{9}$$

in which $H_{min,i}$ is the minimum pressure head at each nodes i [m], Zi is the elevation of node i [m], P_{min} is the minimum required working 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.

3.3.4 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:

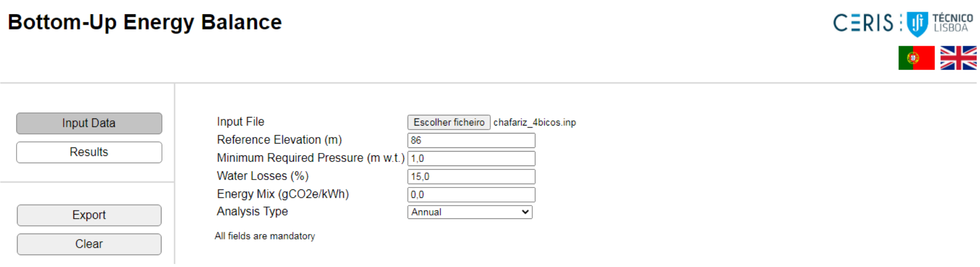
$$E_{WL} = E_{INP} * WL(\%) \tag{10}$$

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.

3.3.5 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 an 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. Figure 3-6 shows the required input values in order to obtain the energy balance using BEEPANET.

After the garden network is upload in EPANET 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. Figure 3-7 shows an example of the BEEPANET output. The BEEPANET tool is still under development in CERIS.

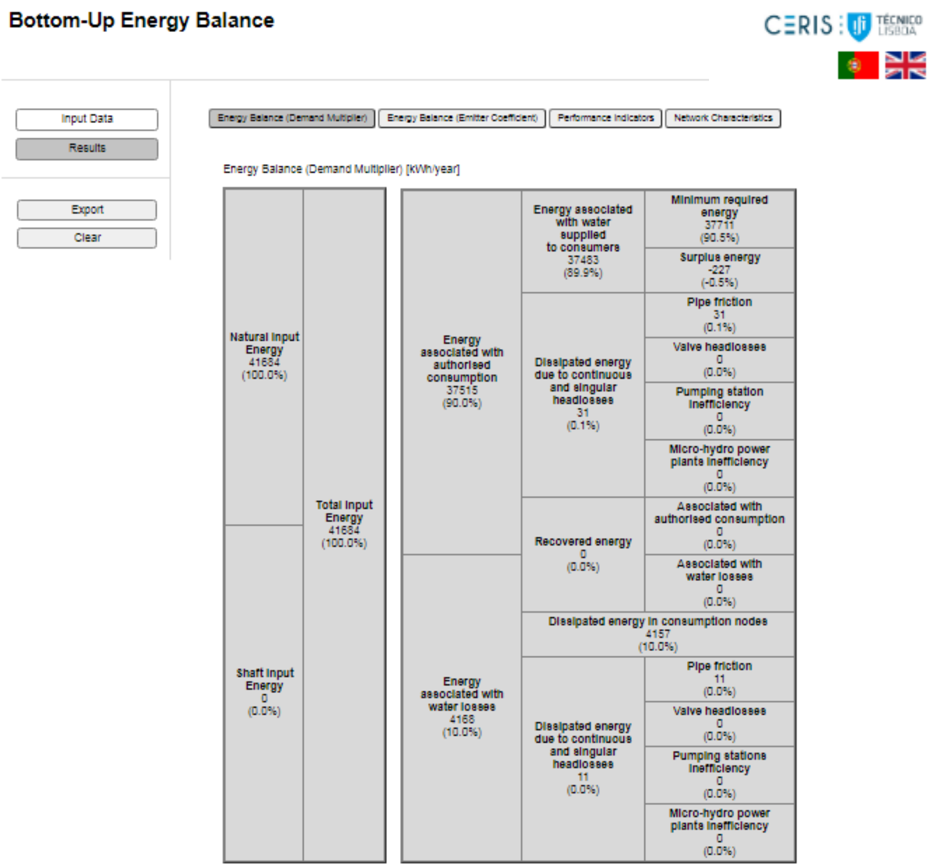


Bottom-Up Energy Balance

Input File: Escolher ficheiro chafariz_4bicos.inp
Reference Elevation (m): 86
Minimum Required Pressure (m w.t.): 1,0
Water Losses (%): 15,0
Energy Mix (gCO2e/kWh): 0,0
Analysis Type: Annual

All fields are mandatory

Figure 3-6 Screenshot of the BEEPANET input sheet.



Bottom-Up Energy Balance

Energy Balance (Demand Multiplier) [kWh/year]

Natural Input Energy 41684 (100.0%)	Total Input Energy 41684 (100.0%)	Energy associated with authorised consumption 37515 (90.0%)	Energy associated with water supplied to consumers 37483 (89.9%)	Minimum required energy 37711 (90.5%)
				Surplus energy -227 (-0.5%)
			Dissipated energy due to continuous and singular headlosses 31 (0.1%)	Pipe friction 31 (0.1%)
				Valve headlosses 0 (0.0%)
				Pumping station inefficiency 0 (0.0%)
				Micro-hydro power plants inefficiency 0 (0.0%)
Shaft Input Energy 0 (0.0%)			Recovered energy 0 (0.0%)	Associated with authorised consumption 0 (0.0%)
		Energy associated with water losses 4168 (10.0%)		Associated with water losses 0 (0.0%)
			Dissipated energy in consumption nodes 4157 (10.0%)	
			Dissipated energy due to continuous and singular headlosses 11 (0.0%)	Pipe friction 11 (0.0%)
				Valve headlosses 0 (0.0%)
				Pumping stations inefficiency 0 (0.0%)
				Micro-hydro power plants inefficiency 0 (0.0%)

Figure 3-7 Screenshot of the BEEPANET output

3.4 Water and Energy performance indicators

3.4.1 Water performance indicator: Irrigation Efficiency

From the water balance components calculation it is possible to obtain a water performance indicator related with irrigation efficiency. The performance indicator Irrigation efficiency, IE, was established and calculated, as follows:

$$IE = \frac{LWR}{WC} * 100 \qquad (11)$$

where LWR is the theoretical landscape water requirement [m^3] and corresponds to irrigation needs component in the water balance and WC is the real measured water consumption [m^3], corresponds to the system input volume in the water balance. This performance indicator is the inverse of the Landscape Irrigation Ratio, LIR, proposed by Glenn et al (2015). When LWR is lower than the water consumption, there is an excess of irrigated water (i.e., water is lost).

3.4.2 Energy performance indicators

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

$$E_1 = \frac{E_{INP} - E_{min}}{V_{consumed}} \ [kWh/m^3] \tag{12}$$

This ratio allows the evaluation of the potential of energy reduction per cubic meter of the water volume consumed. It is always positive and should be as low as possible. The consumed volume does not consider water losses.

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

$$E_2 = \frac{E_{INP} - E_{min}}{V_{theoretical}} \ [kWh/m^3] \tag{13}$$

This ratio allows the evaluation of the potential of energy reduction per cubic meter of water effective use. 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 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:

$$E_3 = \frac{E_{INP}}{E_{min}} \tag{14}$$

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 not lower than one which corresponds to providing the minimum required energy.

4 CASE STUDY 1: HISTORICAL GARDENS OF THE NATIONAL PALACE OF QUELUZ

4.1 Introduction

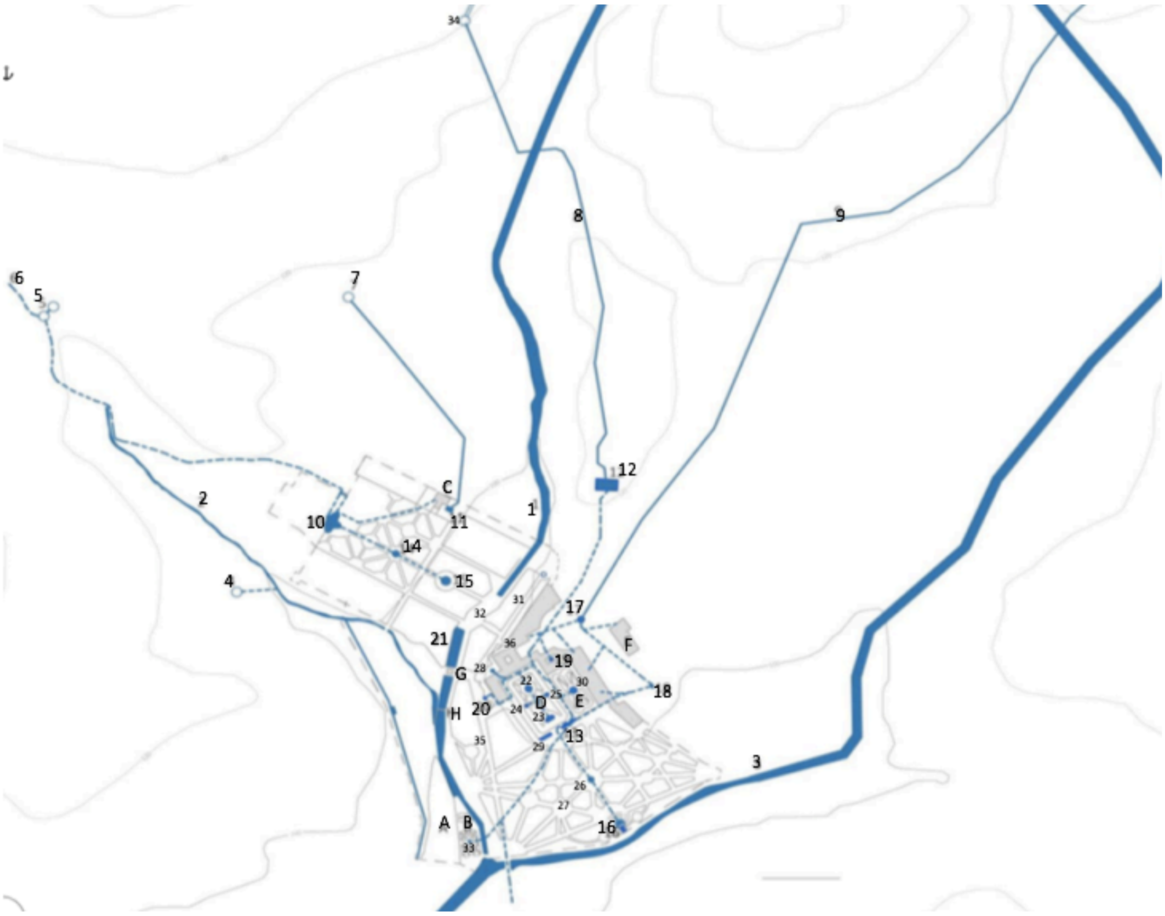
In this chapter, the water uses and consumption in the historical gardens of the eighteen-century Queluz Palace are studied. First, a preliminary characterization of the garden water supply system is presented and, then, the hydraulic model of the system is developed using EPANET software and the hydraulic behaviour of the system is analysed. Lastly, it is applied the bottom-up approach of the yearly energy balance in the three independent hydraulic subsystems of the Queluz gardens.

4.2 Location and characteristics

The National Palace of Queluz and its gardens 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 (Figure 4-1). Besides the need to supply water to the palace, it was also needed to provide water to the gardens and its numerous cascades and decorative fountains, as well as to irrigate the adjacent botanical and horticultural areas. The topography is another characteristic of the site that enables the water transport by gravity from the natural sources (water mines) to the fountains and cascades.

Figure 4-1 Satellite view of the Palace and main water streams: Jamor River (purple), Forcadas stream (green) and Carenque stream (yellow) (source: Google Earth 2020).

A complex hydraulic system was built at the National Palace of Queluz (Figure 4-2) to transport water from the palace surroundings and to distribute the water to the numerous fountains and cascades of the gardens (Rodrigues, 2011; Rodrigues, 2019; Ferro, 1997). 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.



Legend

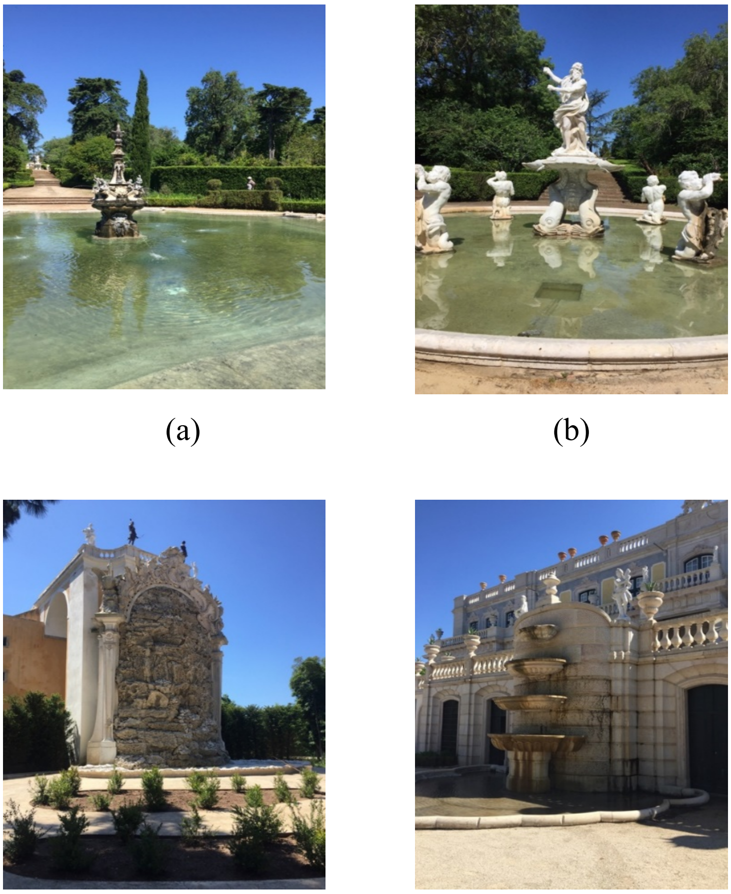
1. Jamor River
2. Forcadas stream
3. Carenque (Carvoeira) stream
4. Terra Grande spring
5. Tijolo e Olheiro spring
6. Tascoa spring
7. São Francisco spring
8. Ponte da Pedrinha aqueduct
9. Príncipe da beira aqueduct
10. Curro tank
11. Lion tank
12. Miradouro tank
13. Hanging garden reservoir
14. Neptune Fountain (Bernini)
15. Medallions fountain
16. Great Cascade
17. Quatro bicas fountain
18. Carranca fountain
19. Lontra terrace fountain
20. Shell cascade
21.Azulejos canal
22. Neptuno fountain
23. Nereide fountain
24-25. Monkey fountain
26- 27. Shell fountain
28. Fountain
29. Gate of fame
30. Dolphin fountain (Malta garden fountain)
31. Embrechados garden fountain
32. Dragon fountain
33. Botanical garden fountain
34. Monte Abrão spring
35. Dragon fountain
36. Palace fountain

A. Horticultural area
B. Botanical garden
C. Byre
D. Hanging garden
E. Malta garden
F. Clock tower
G. Music house
H. Canal gate

Figure 4-2 Scheme of the water supply system of the National Palace of Queluz and its gardens (adapted from Correia 2015).

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 gardens, the species used require a few or none water, i.e., trees, shrubs, no turfgrass was used, which is one of the species that require 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 was reused to irrigate. 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. It will be used

National Palace of Queluz gardens example to illustrate the methodology proposed in 3.2 to calculate the energy balance. Figure 4-3 illustrates some of the fountains and cascades from the National Palace of Queluz.



(a) (b)

(c) (d)

Figure 4-3 Selected fountains and cascades from the gardens of the National Palace of Queluz (a) Neptune fountain (Bernini), (b) Medallions fountain, (c) Great cascade, (d) Shell cascade.

4.2.1 Water supply system description

In the current work, the water supply system of the gardens was drawn using AutoCAD 2020 (Autodesk), based on existing nineteenth century maps (Figure 4-4) and on other information found in literature (*Planta das minas e encanamentos d'agua do Almoxarifado de Queluz*, 1901, Figure 4-4). Regarding the description of water flow path and the pipes materials (iron, lead).

In the lack of information regarding the source of the water supplying the Dragon fountain (see item 35, in Figure 4-2), it was assumed that an additional pipe would connect it to the Shell cascade (see item 20, in Figure 4-2), located nearby and at a higher elevation.

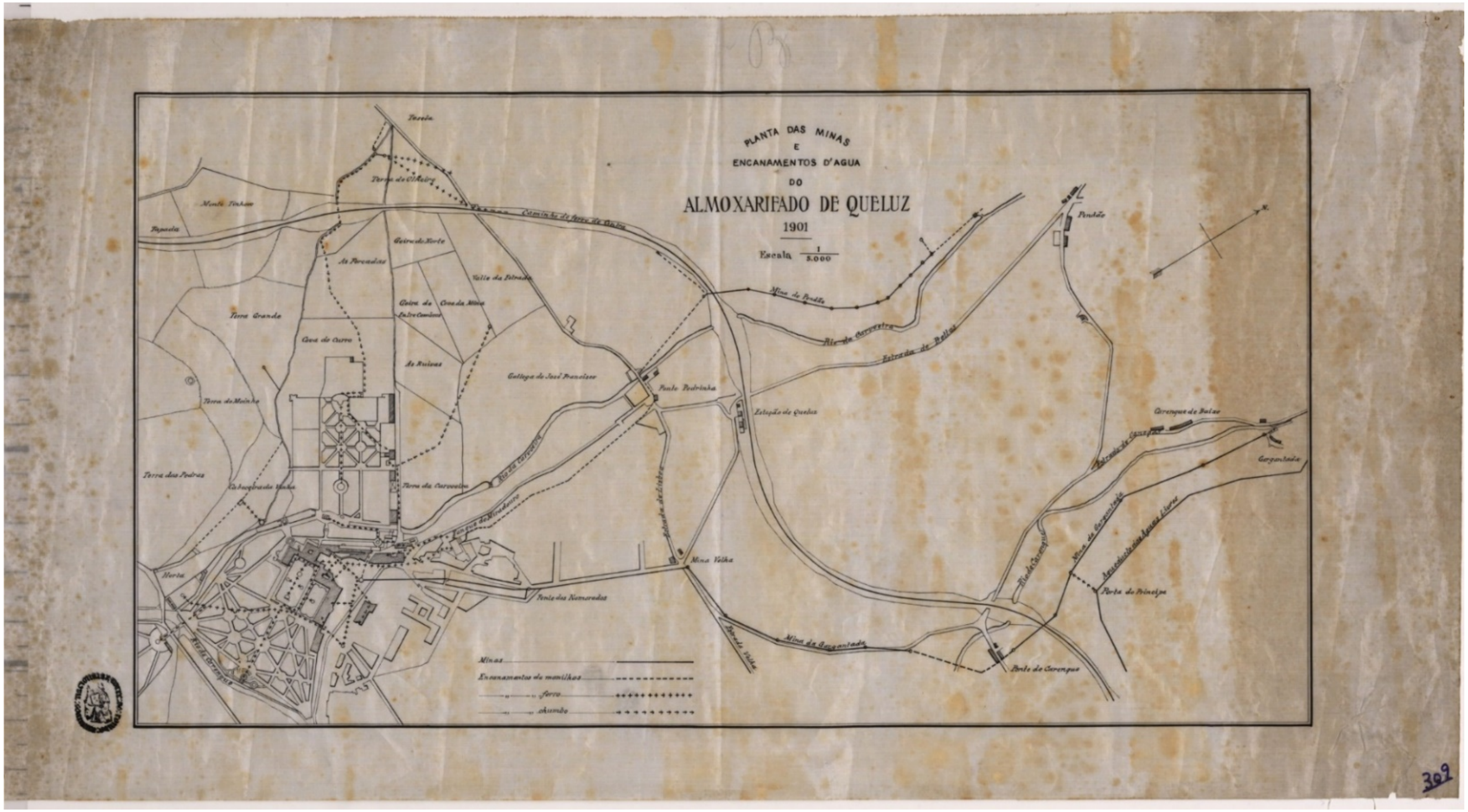


Figure 4-4 Map of Queluz palace and the gardens in 1901.

The water supply system scheme was composed of four main subsystems as presented in Figure 4-5, namely, Terra Grande, Curro, Miradouro and Quatro Bicas subsystems.

Terra Grande subsystem, represented with the purple lines in Figure 4-5, conveyed water from the Terra Grande spring and from Forcadas stream through an open canal to the palace gardens for irrigation of the botanical garden and of the horticultural area. Since the flow in this system is a free surface flow, it does not have any fountains, not being analysed in the scope of this study.

Curro subsystem, represented with the red lines in Figure 4-5, connected Tascoa spring and Tijolo and Olheiro spring to the Curro tank (see 10, Figure 4-5) by means of a lead pipe. Curro tank distributes water to the Neptune fountain (Bernini) (see 14, Figure 4-5) and the Medallions fountains (see 15, Figure 4-5).

Miradouro subsystem, represented with the green lines in Figure 4-5, transported water from several springs located in Monte Abraão and Pendão through Ponte da Pedrinha aqueduct to Miradouro tank (see 12, Figure 4-5). From this tank forward, water is transported through pressurized iron pipes to the fountains of the Hanging and Malta gardens (see 22, 23, 24, 25, 29 and 30, Figure 4-5), ending its path in the Great Cascade (see 16, Figure 4-5).

Quatro Bicas subsystem, represented with the blue lines in Figure 4-5, conveyed from Carenque stream flows with free surface through Principe da Beira aqueduct to Quatro Bicas fountain (see 17, Figure 4-5). From there, a pressurized pipe system transported water to the palace, to the kitchen, the Embrechados garden, the Lontra terrace fountain, the church and the clock tower (see 19, 31 and 36, Figure 4-5). Later on, in 1896, a pipe was built connecting Quatro Bicos fountain and Carranca fountain (see 18, Figure 4-5). From there, water would flow to the reservoir underneath the Hanging garden and then to the botanical garden (see 33, Figure 4-5).

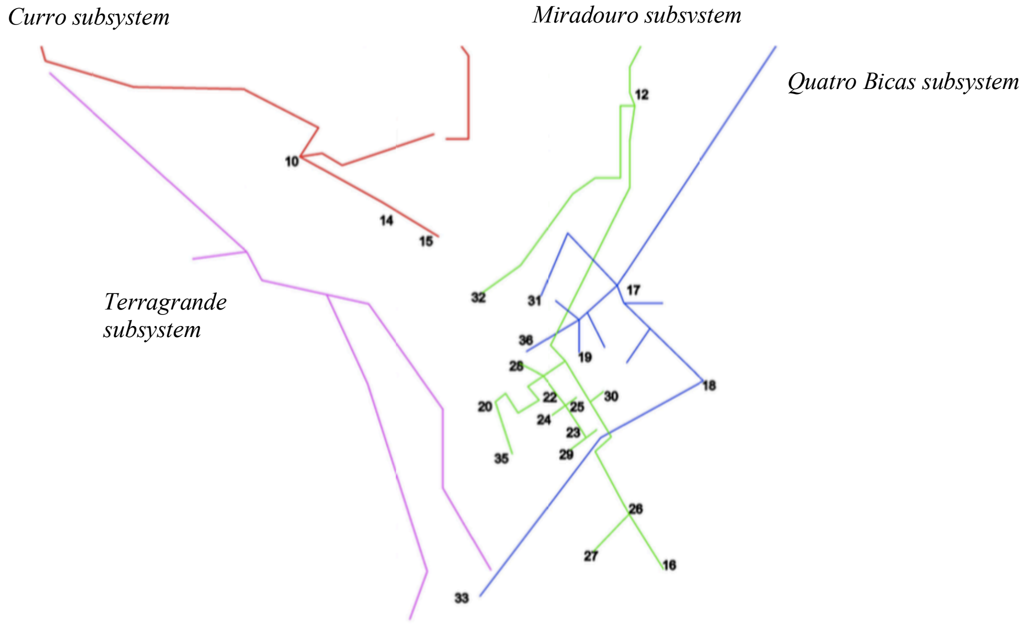


Figure 4-5 Schematic representation of the water supply and irrigation system of the National Palace of Queluz.

4.3 Hydraulic modelling of the garden water supply system

The three pressurized subsystems (Curro, Miradouro and Quatro Bicas) were drawn in AutoCAD 2020 and converted into an EPANET model (Rossman, 2000). Terra Grande subsystem was not analysed, since water flows in an open canal and was used for irrigation purposes only, not having any fountains or cascades.

Elevation data were obtained from Google Earth platform. In the lack of more reliable information and based on photographs of the iron water pipes during a rehabilitation intervention that was carried out recently (Figure 4-6 a and b), 150 mm diameter was considered for all pipes of the water supply system of the palace gardens. These pipes were assumed to be made of cast iron with a Hazen-Williams roughness coefficient of 130 $m^{0,37}s^{-1}$ (this coefficient is relevant to calculate friction losses in pipes).

(a) (b)

Figure 4-6 (a) Unearthed water pipes from the gardens of the National Palace of Queluz (b) rehabilitation works at Malta garden.

Each of the subsystem 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), as will be explained next, since no flow rate or water demand data were found in literature.

The decorative fountains and cascades were divided into two main types, according to the area of the lake and to the number of water spurts (Table 4-1). Type I is associated with smaller lake surface area (between 3 and 55 m^2) and few water spurts (less or equal than four), with the exception of Gate of Fame which was considered to be Type I because it does not have any water spurts. Type II is associated with a larger area (higher than 55 m^2) and/or higher number of water spurts (more than four), with the exception of Nereide fountain and shell fountain, due to the high number of water spurts. Cascades were also considered Type II due to their large size. Table 4-1 shows the fountains and cascades associated with each type as well as their estimated water surface area and number of spurts.

Table 4-1 Categorization of each fountain and cascade of the National Palace of Queluz.

Type I			**Type II**		
Fountain name	Area (m^2)	Water spurts (no.)	Fountain name	Area (m^2)	Water spurts (no.)
Lontra terrace fountain	14	⩽ 4	Neptune fountain (Bernini)	92	> 4
Carranca fountain	11		Medallions fountain	94	
Monkey fountain	11		Great Cascade	-	
Fountain	5		Shell cascade	-	
Gate of fame	88		Neptune Fountain	62	
Dolphin fountain	55		Nereide fountain	35	
Dragon fountain	12		Shell fountain	11	
Embrechados garden fountain	34				
Botanical garden fountain	35				
Palace fountain	3				

4.3.1 Assessment of the water consumption at the gardens

Three demand scenarios were established and analysed (Table 4-2) to quantify the water consumed in the gardens for ornamental purposes only, based on known water flowrates at the domestic level. A domestic tap has a flow rate between 0.08-0.15 L/s; assuming an average value of 0.1 L/s and considering that type I fountain has 5 spurts (each with a similar consumption as a water tap) and type II has 8 spurts, this would result in a total demand of 0.5 and 0.8 L/s, respectively. These consumptions correspond to scenario 1. The other two scenarios 2 and 3 consider to an increase of 0.5 and 1 L/s on the previous values. In these scenarios, all fountains and cascades were simultaneously consuming water, which corresponds to the most critical situation in terms of water consumption. The water consumed at the fountains was compared with the available water in the surrounding water sources.

Table 4-2 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

The total water flow rate consumed at the gardens for aesthetic purposes for each of the three analysed scenarios calculated by EPANET is presented in Table 4-3. These values are compared with the available water flow rate in the natural sources surrounding the National Palace of Queluz, which is, on average, 32 L/s, including the summer period (Henriques *et al.*, 2006).

Table 4-3 Total flow rate consumed in the subsystems for each scenario.

Subsystem	**Water consumption (L/s)**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Curro	1.6	2.6	4.6
Miradouro	8.3	14.8	27.8
Quatro Bicas	2.5	5.0	10.0
Total	12.4	22.4	42.4

Assuming the water spurts of the all the fountains and cascades in the garden function simultaneously during 24 hours in a day the water consumption of the gardens would be 1071 m^3, 1935 m^3 and 3663 m^3, for scenario 1, 2 and 3, respectively.

The most water demanding conditions correspond to scenario 3 (42.4 L/s) which exceed the local average available flow-rate (32 L/s). This suggests that water was continuously stored in the upstream tanks to cope with consumption needs of the ornamental fountains, which were operated during a limited number of hours per day, and those of the irrigation. This results show that the water consumption at the gardens for decorative purposes would be in the range of 12.4 to 42.4 L/s, or 45 to 152 m^3 per hour.

4.3.2 Pressure-head and hydraulic performance of the systems

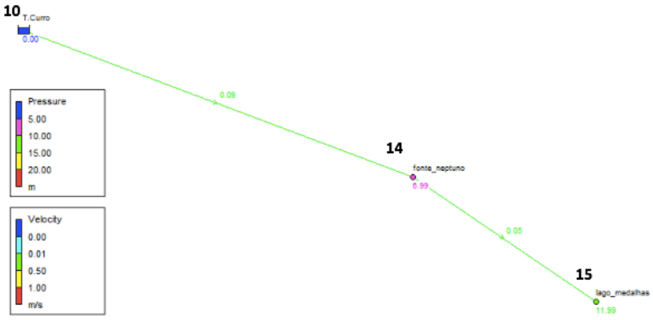
The three scenarios were simulated using EPANET for the three pressurised pipe systems, namely, Curro subsystem, Miradouro subsystem and Quatro Bicas subsystems. Results are presented in the following paragraphs.

Curro subsystem

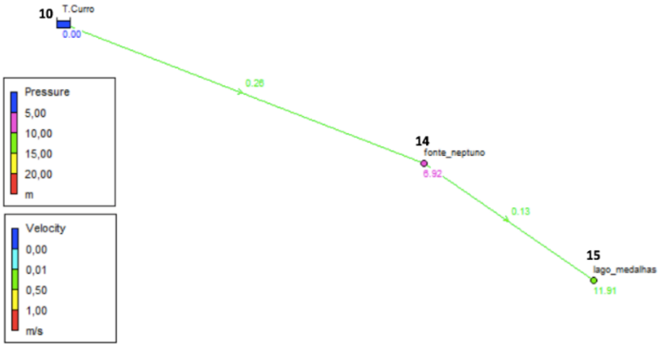
Figure 4-7 presents the numerical results obtained for Curro subsystem in terms of pressure-head at the nodes of the two extreme operating scenarios 1 and 3. Results show that the available pressure-head at the two fountains – Neptune (Bernini) and Medallions fountains – are of 7.00 and 12.00 m, respectively (Figure 4-5). These values correspond to the maximum height reached by the water jets at the fountains, since the nodal pressure-head, $h = p / \gamma$, is converted into water velocity in the spurts according to Torricelli velocity law, $u = \sqrt{2gh}$, in which *u* is fluid velocity (m/s), *g* is gravity acceleration (m/s^2), *h* is pressure-head (m), *p* is pressure (Pa) and γ is water specific weigh.

Additionally, the small water demands at the fountains and cascades in both scenarios, though operating simultaneously, transported in the 150 mm pipe diameters result in low flow velocities in the pipes and very low head losses between the tank and the fountain.

Differences in the pressure-head and in the flow velocity in scenarios 1 and 3 are minimal. For instance, pressure head at node15 is 11.99 m in scenario 1 and 11.91 in scenario 3.



(a)



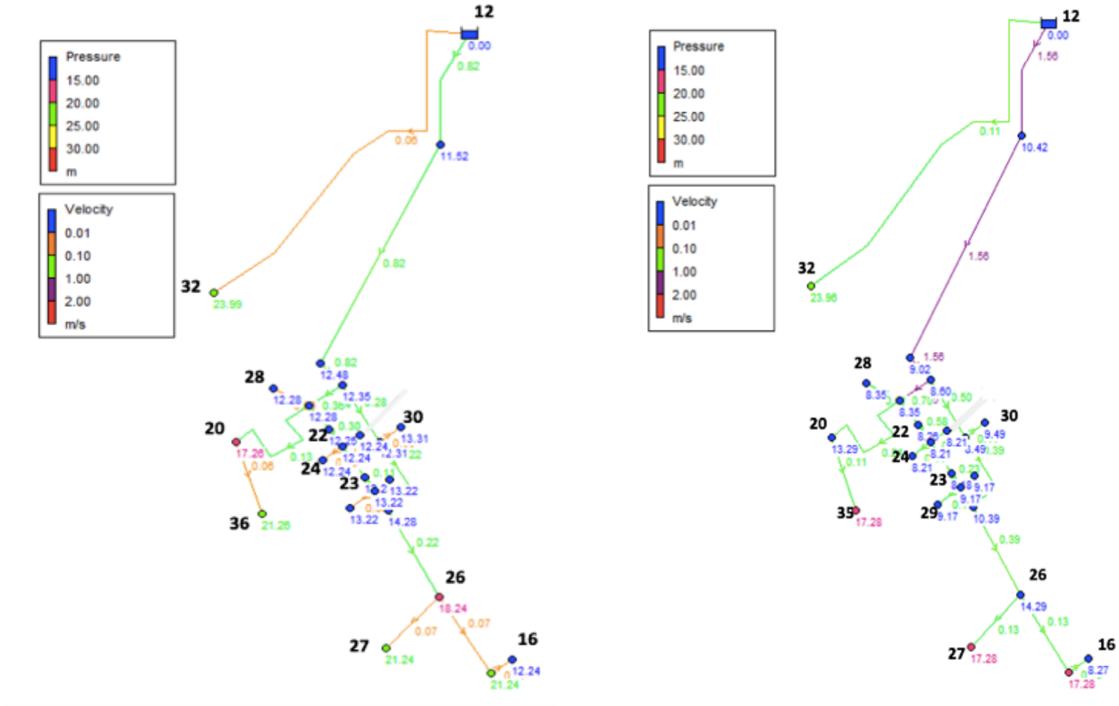
(b)

Figure 4-7 Pressure-head at the fountains and cascades and flow velocity in the pipes in Curro Subsystem for (a) scenario 1 and (b) scenario 3.

Miradouro subsystem

Figure 4-8 presents the numerical results obtained for Miradouro subsystem in terms of pressure-head at the nodes for the two extreme operating scenarios 1 and 3. These results show that the pressure-head at the main fountains Neptune, Nereide and Dolphin and at the top of the Great Cascade are in the range of 8.00 to 13.00 m, depending on water demand scenario considered (Figure 4-8). This subsystem includes one of the principal groups of fountains (fountains located in Pensil and Malta garden) and the Great cascade. The results of the modelling demonstrate that the water can flow by gravity in the pressurized piped system, as the pressure head is enough for the water to reach all fountains, including the tank on top of the Great Cascade (see node 16, Figure 4-8), since the available pressure head is 12.24 and 8.24 m in scenarios 1 and 3, respectively.

These results also show that the Great Cascade can be supplied by the Miradouro tank (see node 12 in Figure 4-8) but could not be supplied by the Curro Tank (see node 10, Figure 4-7) as the elevation difference between the two locations is small (close to 6 m) and would barely be enough for the water to reach the top of the Great Cascade.



(a) (b)

Figure 4-8. Pressure-head at the fountains and flow velocity in the pipes of the Miradouro subsystem for (a) scenario 1 and (b) scenario 3

Figure 4-9 shows a photograph of the dolphin fountain (see 30 in Figure 4-8) indicating the potential height of the water jet (available pressure head is 9.49 m for scenario 3), which illustrates that the water jets could go almost as high as the palace height (estimated to be around 10 m). This fact was described by Pires (1925-1926): “it threw water over the roof of the palace”[1].

Figure 4-9 Dolphin fountain (30), located in Malta garden. Represented in a blue arrow is the height of the water jet in comparison to the height of the palace.

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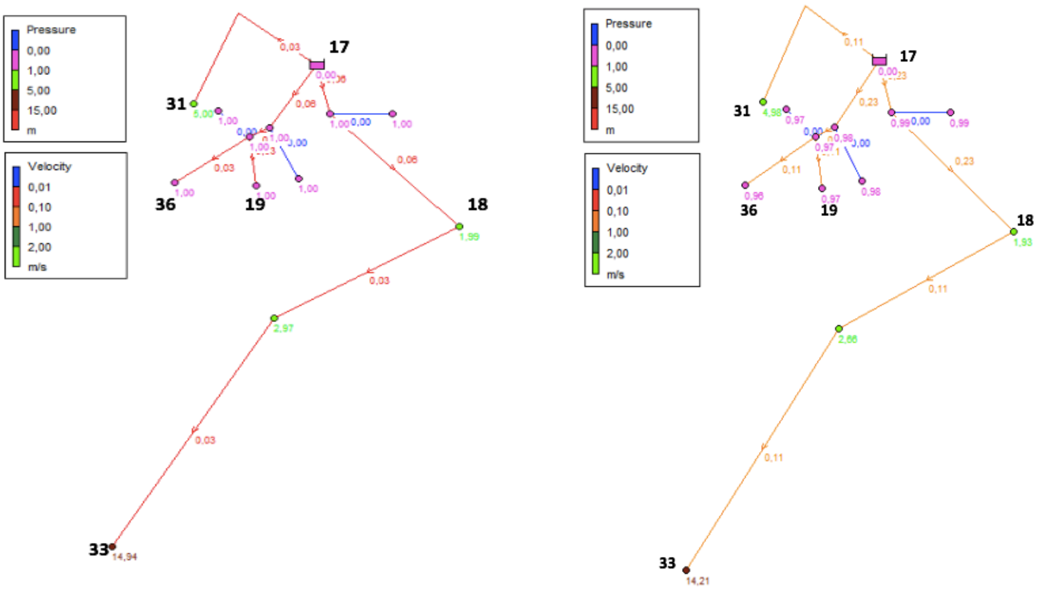
[1] Original text in portuguese: “vomitava água por cima do telhado do palácio” (Pires, 1925-1926)

There are other descriptions in Pires (1925-1926) of the water show created by the several ornamental fountains and the Great cascade that corroborate the height of water jets, as the following: “The gardens offered a show and a magnificence never seen. From all the fountains, water was drawn in many ways, at the bottom of the park the cascade showed all its wonderful effect”[2] and “With the prince they went for a walk in the gardens, where the water spurts from the fountains were on, which caused them a big admiration for its magnificence and greatness”[3]. These descriptions are in agreement with the hydraulic calculations carried out herein, demonstrating that the water jets in the fountains and cascades were indeed very high and created a wonderful water show.

Quatro Bicas subsystem

Figure 4-10 presents the numerical results obtained Quatro Bicas subsystem in terms of pressure-head at the nodes of for the two extreme operating, scenarios 1 and 3. In most of the Quatro Bicas subsystem, the available pressure head at the consumption nodes is low (lower than 3 m) for both scenarios, except in the fountain at the botanical garden (see 33 in Figure 4-10). This is due to the small elevation difference between the water source (the Quatro Bicas fountain) and the water consumption locations. However, the available head in Quatro Bicas subsystem is enough for the water uses in this system, as it does not include the main fountains and lakes of the gardens.



(a)

(b)

Figure 4-10 Pressure-head at the fountains and flow velocity in the pipes of the Quatro Bicas subsystem for (a) scenario 1 and (b) scenario 3

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[2] Original texto in portuguese: “os jardins ofereciam um espetáculo e uma magnificência nunca vistos pelos arrais. De todos os lagos a água repuxava de variadas maneiras, ao fundo do parque a cascata mostrava todo o seu maravilhoso efeito(...)” (Pires, 1925-1926)

[3] Original texto in portuguese: “Com o Príncipe foram dar um passeio pela quinta, tendo mandado abrir os repuxos dos lagos, que lhes causaram grande admiração, pela sua magnificência e grandeza” (Pires, 1026)

The water demand increase from scenario 1 to 3 result in an increase of the water velocity in the pipes and to a decrease in available pressure head at the fountains. However, the simulations carried out in EPANET show that the system can cope with such increase in water demand and still be able to supply the fountains and the cascades. Overall, the results show that the design of the complex water supply system of the gardens allows it to cope with great variations in water demand, such as the increase in demand from scenario 1 to 3.

4.4 Application of the proposed energy balance

The energy balances of the three independent subsystems of the gardens of the National Palace of Queluz were calculated by using the BEEPANET. Initial values for the input variables were set for each subsystem (Table 4-4).

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 was 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. In Miradouro subsystem, the minimum required pressure head is 9 m, in order to assure that the jet height at the Dolphin fountain could reach the roof of the Palace. Lower values are assumed for the Curro and Quatro bicas subsystems because the water jets in these fountains are smaller (2 and 1 m were considered). For Quatro bicas subsystem only 1 m of minimum pressure head was established because the fountains belonging to this subsystem are the ones in which the water jets reach the lowest heights.

The percentage of water losses had to be assumed, because there was no data available regarding leakages. Hence, based on the average water losses of a urban supply water system, which are of around 20-30% (Covas et al., 2008), a smaller value of 15% was considered, as the garden supply system is considerably smaller and simpler than a urban supply system.

The energy mix is zero due to the inexistence of electrical energy consumption in the gravitational supply system.

Table 4-4 Input values of the BE of each independent subsystem of the Queluz Palace.

Input values	**Curro Subsystem**	**Miradouro Subsystem**	**Quatro bicas Subsystem**
Reference elevation (m)	94	91	86
Minimum required pressure (m)	2	9	1

The energy balances obtained for the three subsystems are presented in Tables 4-5, 4-6 an 4-7. Highlighted in light blue are all the components calculated using the bottom-up approach. This is a yearly balance that assumes the water is running 24 hours per week during one year. Minimum required energy for irrigation was not computed because these sub-systems only supply the ornamental fountains and cascades. Minimum required energy for other uses, in this case study, is then related with the minimum energy required for the water spurts in the ornamental fountains to achieve a certain height.

Table 4-5 Energy balance of the Curro subsystem (kWh/year).

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%)		

Table 4-6 Energy balance of the Miradouro 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%)		

Table 4-7 Energy balance of the Quatro bicas subsystem (kWh/year).

Natural input energy (E_N) 157 (100%)	Total system input energy (E_{INP}) 157 (100%)	Energy associated with effective use (E_{EU}) 134 (85%)	Energy associated with water supplied to consumers (E_{SUP}) 132 (84%)	Minimum required energy for irrigation (E_{min})
				Minimum required energy for other uses ($E_{min,o}$) 100 (63.5%)
				Surplus energy (E_{SUR}) 32 (20.5%)
			Dissipated energy (E_{DIS}) 1 (1%)	Pipe friction ($E_{diss,f}$) 1 (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}) 23 (15%)		

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 (see 14 and 15, Figure 4-2) of 2 m height. I

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.

For Quatro bicas, subsystem the percentage of surplus energy is higher than for the Miradouro subsystem but lower than for Curro subsystem.

Dissipated energy is related with the pipe friction since these subsystems do not have valves or pumps. The highest percentage of dissipated energy is for the Miradouro Subsystem (19.1%) which is the longest system in terms of pipes and the system with the largest number of fountains. On contrary, the least complex subsystem and with the smallest number of fountains (therefore less pipes) is Curro subsystem, having the lowest percentage of dissipated energy (0.6%). Quatro bicas subsystem has a higher length than Curro but lower than Miradouro subsystem and has less fountains and, therefore, the percentage of dissipated energy is only 1%.

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. For a better comparison between each subcomponent of the energy balances the following Figure 4-11 presents the results for each of the three studied subsystems of the National Palace of Queluz.

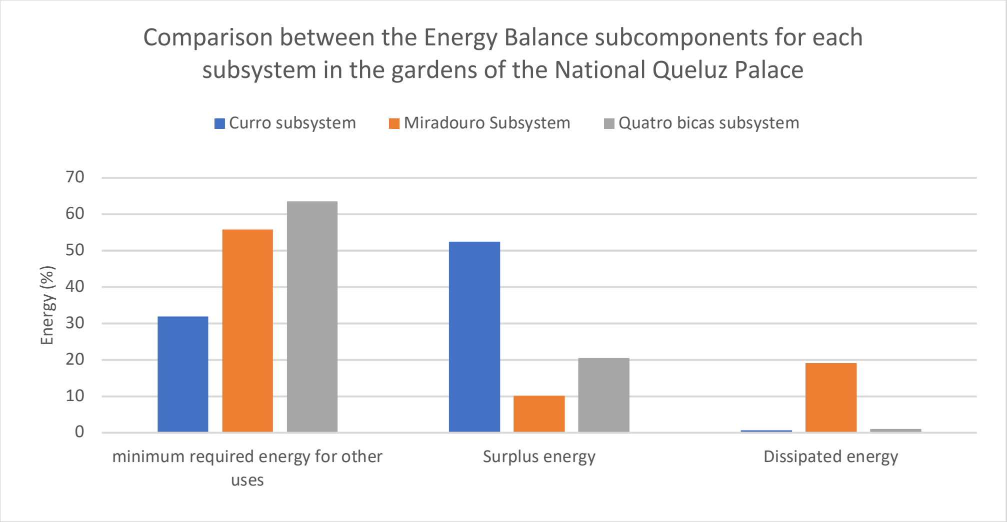


Figure 4-11 Energy Balance subcomponents for each subsystem in the gardens of the National Queluz Palace.

4.5 Energy Efficiency Performance Indicators

Another type of output from the energy balance is the performance indicators associated with each subsystem (Table 4-8).

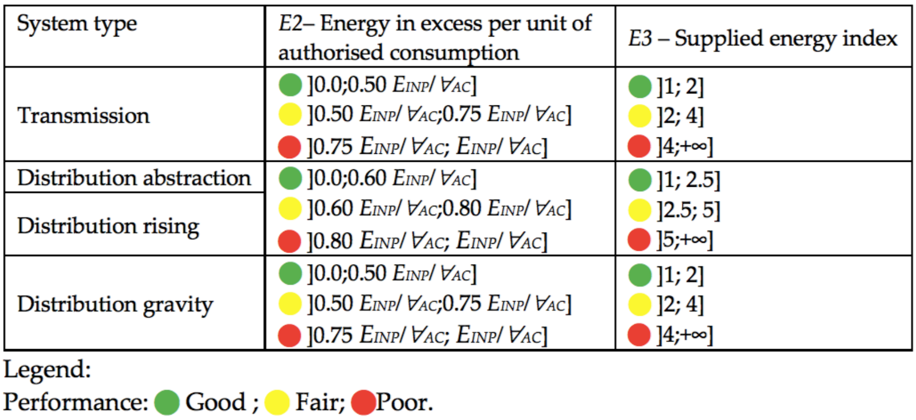
E1 and E2 indicators do not vary much between the three subsystems. The difference between these two indicators is related with water losses, thus, these indicators will only be very different if the water losses are very high, which is not the case in these subsystems.

Curro subsystem has the worst E3 performance indicator because energy supplied is much higher than minimum required energy; this is in agreement with the results of Table 4-4 in which the surplus energy corresponds to 52.5%; this system has a lot of energy that could be used to supply water to other fountains located near the already built fountains supplied by the Curro reservoir. Miradouro and Quatro bicas subsystems have both E3 values close to one, indicating that the energy supplied to the fountains is close to the minimum one.

Table 4-8 Performance indicators of each subsystem of National Palace of Queluz.

Performance indicators	Curro Subsystem	Miradouro Subsystem	Quatro bicas Subsystem
E1 (kWh/m^3)	0.02	0.03	0.01
E2 (kWh/m^3)	0.03	0.03	0.02
E3 (-)	3.14	1.79	1.58

In order to assess if these performances are good, fair or unsatisfactory, Mamade (2019) established a table of reference values for performance indicators E2 and E3 for four different system types (see Figure 4-12). The system type that better fits National Palace of Queluz hydraulic system is water distribution by gravity. According to Table 4-8, Curro subsystem has a fair performance in terms of energy efficiency and the other two subsystems have a good performance. When it comes to energy performance E2, the three subsystems are considered to have a good performance.



System type	*E2*– Energy in excess per unit of authorised consumption	*E3* – Supplied energy index
Transmission	🟢]0.0;0.50 $E_{INP}/\forall_{AC}$] 🟡]0.50 $E_{INP}/\forall_{AC}$;0.75 $E_{INP}/\forall_{AC}$] 🔴]0.75 $E_{INP}/\forall_{AC}$; $E_{INP}/\forall_{AC}$]	🟢]1; 2] 🟡]2; 4] 🔴]4;+∞]
Distribution abstraction	🟢]0.0;0.60 $E_{INP}/\forall_{AC}$] 🟡]0.60 $E_{INP}/\forall_{AC}$;0.80 $E_{INP}/\forall_{AC}$] 🔴]0.80 $E_{INP}/\forall_{AC}$; $E_{INP}/\forall_{AC}$]	🟢]1; 2.5] 🟡]2.5; 5] 🔴]5;+∞]
Distribution rising		
Distribution gravity	🟢]0.0;0.50 $E_{INP}/\forall_{AC}$] 🟡]0.50 $E_{INP}/\forall_{AC}$;0.75 $E_{INP}/\forall_{AC}$] 🔴]0.75 $E_{INP}/\forall_{AC}$; $E_{INP}/\forall_{AC}$]	🟢]1; 2] 🟡]2; 4] 🔴]4;+∞]

Legend:
Performance: 🟢 Good ; 🟡 Fair; 🔴Poor.

Figure 4-12 Reference values for energy efficiency indexes E2 and E3 for water supply systems (Mamade 2019).

5 CASE STUDY 2: VALE DO LOBO URBAN GARDEN

5.1 Introduction

The present chapter describes the second case study, the urban green areas of Vale do Lobo. The methodology proposed in Chapter 3 to calculate water balances and energy balances is applied to this case study. Firstly, a preliminary characterization of the case study is presented, followed by the water balance application for the years 2017, 2018 and 2019. Results are presented for the components that were able to be calculated with the available data. Then, the irrigation efficiency is further assessed for the same years and partially for 2020. Improvement measures for water use efficiency are proposed. The energy balance is also applied to the case study and energy performance indicators are calculated and discussed.

5.2 Case study description

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. Infralobo system serves 2353 clients in an area of 510 ha. The utility manages the water infrastructures (about 66 km of water distribution pipes and 54 km of wastewater pipes), urban waste collection and the maintenance of 22 ha of public green areas (Figure 5-1). Infralobo consumed, in 2018, about 266 536 m^3/year of water for irrigation of green areas, which corresponds to about 25% of the total annual billed water volume. The green areas are mainly covered with turfgrass, which requires high irrigation volumes. This is particularly relevant in an arid region like the Algarve, in which the drought is very predominant in summer/spring period and rains during the winter/autumn can be quite scarce depending on the years.

Figure 5-1 Delimitation of the 22 ha of green spaces in Vale do Lobo.(Manso et. al, 2019).

This case study is focused on a specific urban garden (Figure 5-2) of 1.92 ha, which corresponds to around 9% of all the green spaces managed by Infralobo. There are twenty irrigation meters, each of them serves more than one green space. The characteristics of each green space differ (Table A-1 in Appendix A): they can either be a turfgrass area or a flower bed area. In total, the garden comprises

154 green spaces (both turfgrass and flowerbed). The distribution of the meters by the irrigated areas is uneven. While one meter measures the water volumes that are consumed in the irrigation of a green space comprised of one turfgrass area and five flower bed areas, other meter serves only four flower bed areas.

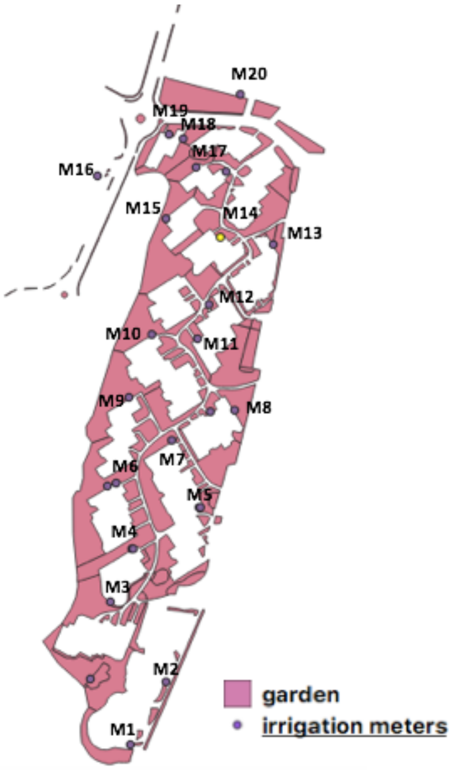


Figure 5-2 Vale do Lobo green areas and water meters.

It is inevitable that an increase in the urban gardens in Mediterranean climate will lead to an increase in used water volume. Water is key for the maintenance of this type of landscapes. The goal is to use as much water as needed, avoiding water losses.

Some photographs of the different irrigated green spaces that are part of the case study (both turfgrass zones and flowerbeds) are presented in Figure 5-3 to illustrate this case study located in Vale do Lobo.

Figure 5-3 Examples of landscaping characteristics in Vale do Lobo.

With the aim of optimizing the irrigation system, Infralobo 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 into automatic. In this sense, there is a continuous optimization of the irrigation schedules, depending on the weather condition, shutting off irrigation if the weather conditions justify it.

The water volume used in the irrigation of the green spaces is quantified hourly through a telemetry system installed in this platform. The controllers allow the automatic management of irrigation schedule, the detection of damage to any electrovalve, the quantification of water consumption, leakage detection in the irrigation system and reports the stats of the systems.

This solution began to be implemented in 2019. Firstly, 19 controllers were implemented, covering 22% of irrigated areas. Currently, a total of 40 controllers are installed, covering 39% of the 22 ha. This 39% includes the case study area, which, since January 2020, had all of its irrigation meters controlled by the controllers.

Each controller is able to control up to 32 electrovalves, since each irrigation meter has less than that number of electrovalves and, for costs reduction, Infralobo decided to group several meters, having in total eight installed controllers, controlling the 20 irrigation meters. The controllers communicate with each other using gateways’s LoRaWAN (Long Range Area Network) using 4G to the Linus server by VPN of the client.

To implement the system, a meteorological station was installed. The station includes six sensors that measure rainfall, solar radiation, wind direction, wind velocity, temperature and humidity.

5.3 Application of the proposed water balance

The proposed methodology for the water balance calculation in gardens and urban green areas was applied to Vale do Lobo case study, for the years 2017, 2018 and 2019. As referred in the water balance methodology, the first step is to define the system boundaries. In the present case study, the system begins at the main pipe, located close to the irrigation meter M16 (Figure 5-2) and includes all distribution pipes until each irrigation meter. With the data available, it is not possible to include the part of the system that transports water from the irrigation meter until the irrigation sprinkler or dripper. Thus, the water losses related with this part of the distribution system are not quantifiable herein.

5.3.1 System input volume

The water volumes consumed in the system in the years 2017, 2018 and 2019 are presented in Table 5-1, the water consumption for all the three years for each irrigation meter can be consulted in the Appendix A, Tables A-2, A-3 and A-4. These values were calculated by summing the monthly consumption provided by Vale do Lobo for each year. The water in this system is supplied by the public distribution network; thus, the percentage of underground water sources is not applicable herein.

Table 5-1 Vale do Lobo irrigation system: system input volumes (m^3).

	2017	2018	2019
System input volume	31 533	24 349	30 894

System input volume in 2018 is the lowest within the analysed 3-year period. The reason why was that the 2018 was a year with the highest precipitation level (529 mm), compared with 2017 (317 mm) and 2019 (229 mm). In 2019, the year with the lowest precipitation, the system input volume was expected to be the highest, however, that is not the case. This might be related with an increase in awareness regarding efficiency in the water use for irrigation and corresponds to the year when the smart irrigation system began to operate.

5.3.2 Effective use

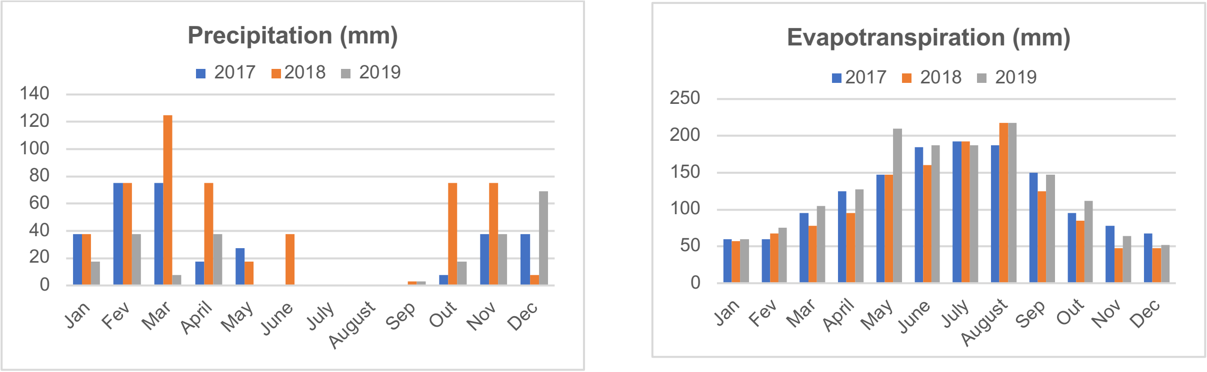
Effective use is divided into consumption for irrigation and consumption for other uses, such as, WC's, restaurants, cafes, fountains, drinking fountains, lakes filling. In the presented case study, there is not consumption for other uses because irrigation network supplies merely water for irrigation.

Consumption for irrigation is the amount of water that is needed to fulfil the plants water requirements (LWR) (the methodology to calculate this value is presented in 3.2.3). Water requirements depend on the type of plants in the gardens and green areas, as well as on the efficiency of the irrigation equipment. In Vale do Lobo case study, sprinkler irrigation is used for turfgrass areas and microirrigation for flowerbed areas. The sprinkler used for the sprinkler irrigation is Rotative sprinkler series 5000 of Rain Bird and for the microirrigation the technology used is micro-sprinklers series MS of Rain Bird and series PSU of Hunter. The type of plant used for the turfgrass area is Escalracho and Football, which for the purposes of the calculous was considered as medium water needs turfgrass. In terms of the flowerbeds, the type of plants used vary a lot, so it was considered a coefficient corresponding to bush and herbaceous medium water needs. The used values for DU_{LQ} and K_L are presented in Table 5-2.

Table 5-2 Lower quarter distribution uniformity (DU_{LQ}) and landscape coefficient for the type of plant in the hydro zone (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

Precipitation, R_a, and evapotranspiration, ET, vary from month to month and with each year as depicted in Figure 5-4. These values were extracted from Instituto Português do Mar e da Atmosfera (IPMA), from Patacão meteorological station, which is a meteorological station located 15 km away from Vale do Lobo, and from the meteorological station located in Vale do Lobo, complete meteorological conditions for the three studied years can be consulted in Table A-6 in Appendix A.



(a) (b)

Figure 5-4 Vale do Lobo irrigation system climatic parameters in 2017, 2018 and 2019: (a) precipitation and (b) reference evapotranspiration.

Figure 5-4(a) shows that precipitation values significantly vary from year to year, even though it rains more during the winter season and less (even almost zero) during summer season (from June to September). Some years during spring, these values increase, for example, in March and April 2018 it precipitated much more comparing with March and April 2019. In terms of evapotranspiration, the difference between the homologous months of each year is negligible. Also, the evapotranspiration is higher during summer season, as expected (Figure 5-4b).

Taking into consideration both climatic parameters, there is a significant difference in the weather conditions from year to year; the weather is getting more unstable, reason why irrigation systems cannot operate based on previous year predictions. Instead, they should be based on the periodical measurement meteorological conditions and irrigation must be adapted to the real plants water needs. This will lead to an increase in the efficiency of irrigation systems and to a decrease of the water use and of the potable water bill.

The Table 5-3 presents the landscape water requirements calculated for the years 2017, 2018 and 2019. 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 5-3 Vale do Lobo irrigation system: effective use for the years 2017, 2018 and 2019 (m^3).

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

5.3.3 Water losses

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 possible thefts or illicit uses of water, which were considered zero because this is a resort with extremely high security. Metering inaccuracies were considered to be 2% of the system input volume for the three years. It was not possible to calculate in detail water losses due to irrigation losses and network real losses. The approach followed herein was to subtract apparent losses and effective use from the system input volume. The result represented the total of water losses due to evaporation, deep percolation, run off, as well as due to losses in the irrigation network. Table 5-4 presents the water losses for Vale do Lobo during the years 2017, 2018 and 2019.

Table 5-4 Vale do Lobo irrigation system: water losses estimation for the years 2017, 2018 and 2019

	2017	**2018**	**2019**
Irrigation losses & network real losses (m^3)	13 469	10 002	8 751
Metering inaccuracies (m^3)	631	487	618

Irrigation losses and network real losses decreased from 2017 (13 469 m^3) to 2019 (8 751 m^3), thus, the amount of water not used for irrigation and wasted decreased in this period. This can be the result of an increased efficiency of Vale do Lobo irrigation system by using the smart irrigation system (SIS), mainly due to the reduced water used for irrigation.

5.3.4 Water balance and performance indicators

Water balances for the case study in the years 2017, 2018 and 2019 are presented in Tables 5-5, 5-6 and 5-7. Water volumes are presented in m^3 and in percentage of the input volume. Highlighted in light blue are the components that could be able to be calculated in the water balance. It was not possible to separately calculate irrigation losses and network real losses, reason why these two were coupled in the balance.

Table 5-5 Water balance applied to Vale do Lobo for the year 2017.

System input volume 31 533 m^3 (Network supply)	Effective use 17 433 m^3 (55 %)	Consumption for irrigation 17 433 m^3 (55 %)	Irrigation needs 17 433 m^3 (55 %)
		Consumption for other uses 0 m^3	wc's, restaurant 0 m^3
			Drinking fountain 0 m^3
			Lakes filling 0 m^3
	Water losses 14 099 m^3 (45%)	Apparent losses 631 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 631 m^3 (2%)
		Irrigation loses & Network real losses 13 469 m^3 (43%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate tanks (-)

Table 5-6 Water balance applied to Vale do Lobo for the year 2018.

System input volume 24 349 m^3 (Network supply)	Effective use 13 860 m^3 (57 %)	Consumption for irrigation 13 860 m^3 (57 %)	Irrigation needs 13 860 m^3 (57 %)
		Consumption for other uses 0 m^3	wc's, restaurant 0 m^3
			Drinking fountain 0 m^3
			Lakes filling 0 m^3
	Water losses 10 489 m^3 (43%)	Apparent losses 487 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 487 m^3 (2%)
		Irrigation losses & Network real losses 10 002 m^3 (41%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate reservoirs (-)

Table 5-7 Water balance applied to Vale do Lobo for the year 2019.

System input volume 30894 m^3 (Network supply)	Effective use 21 525 m^3 (70 %)	Consumption for irrigation 21 525 m^3 (70 %)	Irrigation needs 21 525 m^3 (70 %)
		Consumption for other uses 0 m^3	wc's, restaurant 0 m^3
			Drinking fountain 0 m^3
			Lakes filling 0 m^3
	Water losses 9 369 m^3 (30%)	Apparent losses 618 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 618 m^3 (2%)
		Irrigation losses & Network real losses 8 751 m^3 (28%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate reservoirs (-)

Obtaining the water balance for the reference periods (2017, 2018 and 2019) allowed the quantification of the percentage of effective use and of water losses through time (Table 5-8). 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 5-8 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

The application of the proposed water balance to Vale do Lobo case study illustrates how the methodology can be used to assess the efficiency of the water use in a modern garden at a macroscopic level. Some components of the balance were not estimated either because they were not applicable or not possible to determine with the available data. In any case, it is demonstrated the usefulness of the water balance approach to evaluate the efficiency of the irrigation through time. A throughout analysis of the water use in the case study was also carried out by means of the performance indicator "Irrigation efficiency", as described in the following section.

5.4 Analysis of irrigation efficiency

In the particular case of Vale do Lobo irrigation system, in which water is only used for irrigation, the water use efficiency can be evaluated with further detail. Landscape water requirements (LWR) were compared with water consumption for each irrigated area on a monthly basis. It is important to highlight that there is an uncertainty associated with monthly LWR due to daily variations of the weather and, hence, of the plants water requirements. The performance indicator for irrigation efficiency presented in equation 11 in the methodology section was also calculated, for each month of each year and for all irrigation meters.

5.4.1 Irrigation efficiency in 2017

To analyse irrigation efficiency in 2017, there is a need carry out an analysis at a macro perspective level (i.e., assessing annual and monthly water needs for all the garden) and at a micro perspective level (i.e., verifying each irrigation meter for every month and concluding if there are inefficiency issues related with a specific irrigated area).

Comparing monthly LWR with water consumption, it is observed that, in general, the irrigation practices carried out by Vale do Lobo are adequate, irrigating more during summer period and less during winter time (Figure 5-5). The major problem is related with the quantity of supplied water. Mostly during summer periods (June to September) and early spring, water supplied is much higher than needed. During winter (January to March and October to December) water consumption is much lower, but still higher than LWR. In January, February, March, November and December there was no need to irrigate, as the precipitation is, generally enough to cover the plants water requirements.

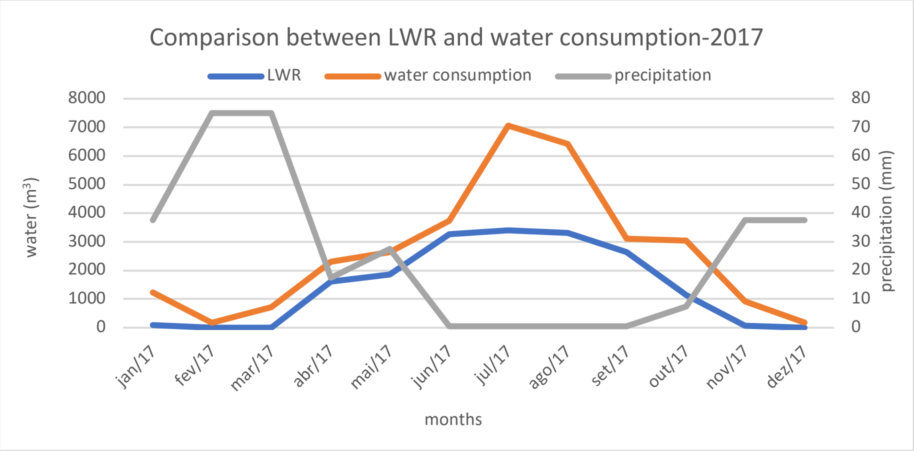


Figure 5-5 Comparison between LWR and water consumption and precipitation during 2017.

To better understand where is the potential for improvement, there is a need of going into a micro analysis, identifying the green areas where irrigation is less efficient (Figure 5-6 and Table 5-9).

Figure 5-6 is organized by decreasing efficiencies, starting in the most irrigation efficient area (M20) until the least efficient irrigated area (M16). Only for areas associated with meters M20 and M5, LWR exceeded water consumption, that is, more water was needed than what was supplied. It is clear in Figure 5-6 that some irrigation meters are supplying much more water than LWR, namely meters M3, M6, M14, M15, M18, M19 and M16. There is a total water saving potential of 14 177 m^3.

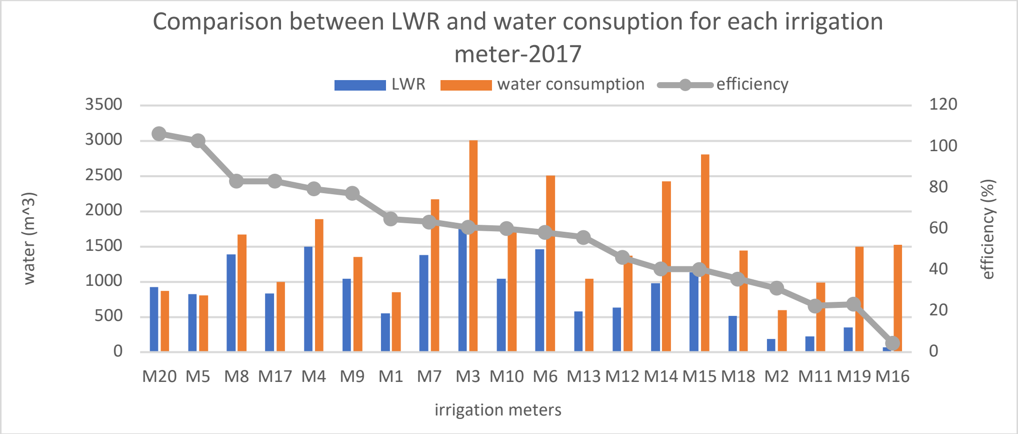


Figure 5-6 Vale do Lobo irrigation efficiency in 2017: comparison between LWR and water consumption at each irrigation meter.

Table 5-9 highlights with different colours the efficiency of irrigation areas according to the following classification:

- Good irrigation efficiency (green): IE ≥ 80%;
- Reasonable irrigation efficiency (yellow): 60%< IE ≤ 80%;
- Inadequate irrigation efficiency (red): IE ≤ 60%;

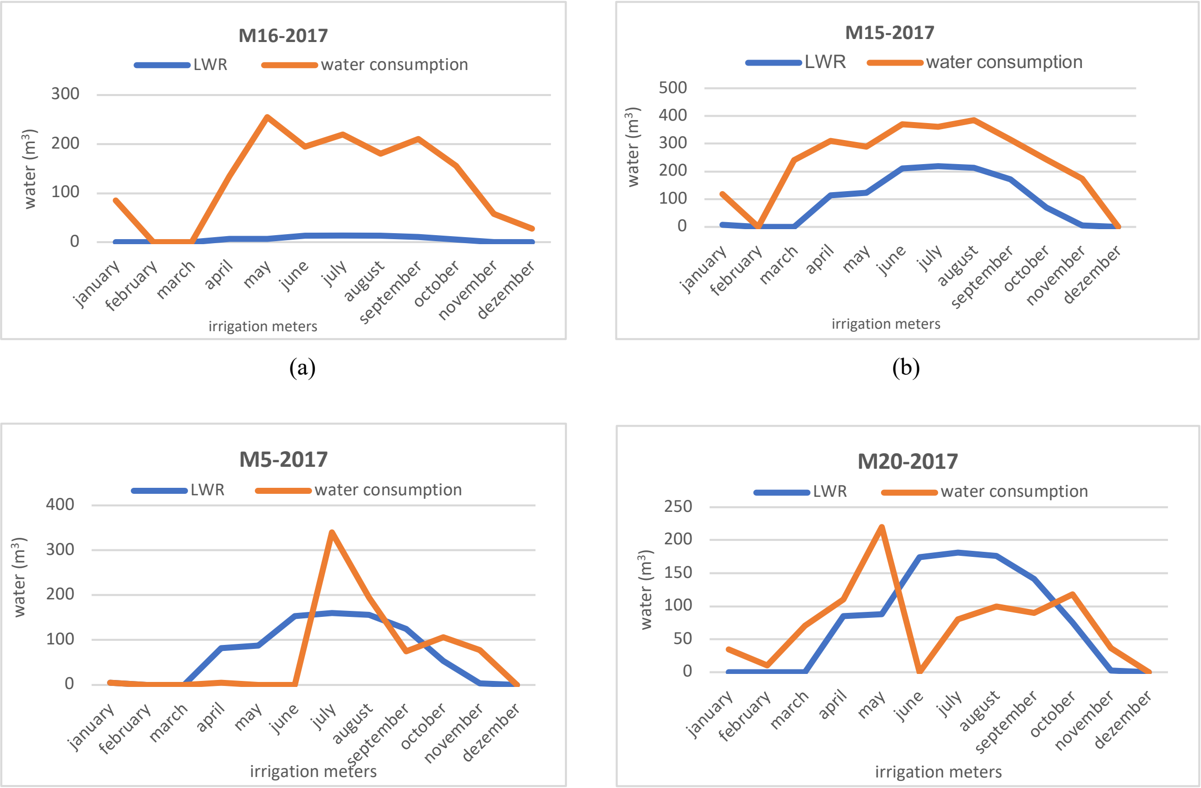
This table shows that there are 10 irrigation meters associated with areas where irrigation efficiencies are lower than 60%, classified as inadequate. Thus, in 2017, 50% of the irrigation meters were associated with inadequate irrigation efficiencies, suppling more water than that was needed. Only 20%

of the irrigation meters are efficient in 2017. In terms of water savings, considering the water tariff as 0.50€/m^3 (normally paid by Vale do Lobo), there is a total water saving potential of 7 088.49€, which is a considerable cost reduction that can be attained.

Table 5-9 Irrigation efficiency associated to each meter (%) and potential water savings (in m^3 and in €) in 2017.

Irrigation meter	**Irrigation efficiency (%)**	**Water savings potential (m^3)**	**Water savings potential (€)**
M1	65	300	150.04
M2	31	408	203.91
M3	61	1 180	590.05
M4	79	389	194.74
M5	103	0	0.00
M6	58	1 048	524.13
M7	63	796	397.82
M8	83	281	140.50
M9	77	309	154.35
M10	60	692	346.20
M11	23	765	382.27
M12	46	738	368.76
M13	56	458	228.79
M14	40	1 443	721.40
M15	40	1 676	837.89
M16	5	1 452	725.75
M17	83	168	83.95
M18	36	926	463.04
M19	23	1 150	574.90
M20	106	0	0.00
Total		14 177	7 088.49 €

The low efficiencies are mostly due to excessive irrigation during summer months. Figure 5-7(a) shows the monthly variation of IE in meter M16, in which it is clear the discrepancy between LWR and water consumption from May to September. The similar behaviour is observed in meters M15 which present higher water consumption compared with LWR for the months from March to November (Figure 5-7b). Figure 5-7(c),(d) show examples of the LWR and water consumption variation in the two best efficiency irrigation meters M5 and M20; in these meters, water consumption is of the same order of magnitude of LWR, whereas in M16 and M15, it is significantly higher. In M5 area, there were only two periods of excessive water irrigation – from July to August and from October to November - being the difference in the last one between LWR and water consumption is lower (Figure 5-7c). The M20 area was not sufficiently irrigated during summer (from June to September). The highest efficiencies of these two irrigation meters, M5 and M20, result from the subirrigation in some periods that compensates the periods in which irrigation was excessive.



(a) (b)

(c) (d)

Figure 5-7 Vale do Lobo irrigation efficiency in 2017: LWR versus water consumption for the irrigation meters (a) M16, (b) M15 (c) M5 and (d) M20.

5.4.2 Irrigation efficiency in 2018

Figure 5-8 shows that, in 2018, LWR and water consumption during winter were very similar. The major difference stands for August and October. Yet, the two profiles are closer than in 2017 and, in August (normally the warmest month), the water saving potential is lower (2 862 m^3) compared with the water saving potential of August 2017 (3 117 m^3).

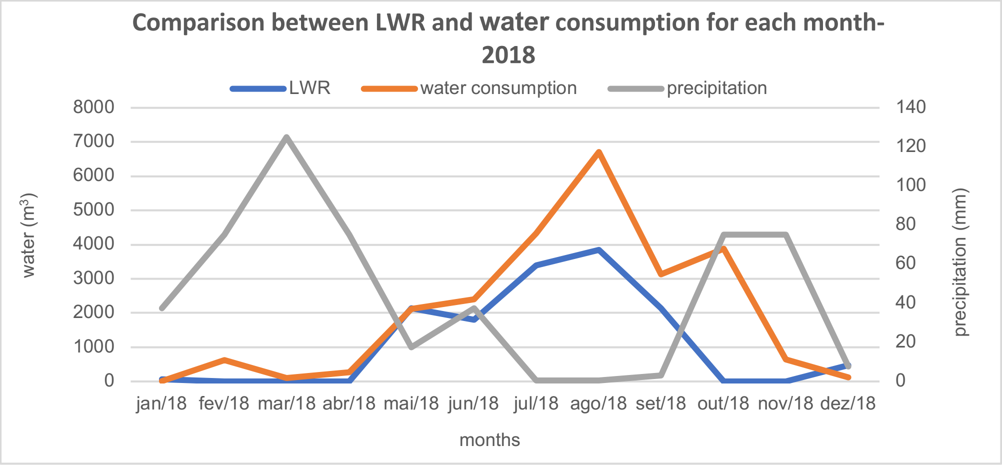


Figure 5-8 Comparison between LWR and water consumption and precipitation during 2018.

Once again, yearly water consumption is higher than LWR for most irrigated areas, except for the ones associated to meters M20 and M17. Comparing Figure 5-9 with the one for 2017 (Figure 5-6), it is observed that the difference between LWR and water consumption for some meters decrease which is a good sign in terms of water savings.

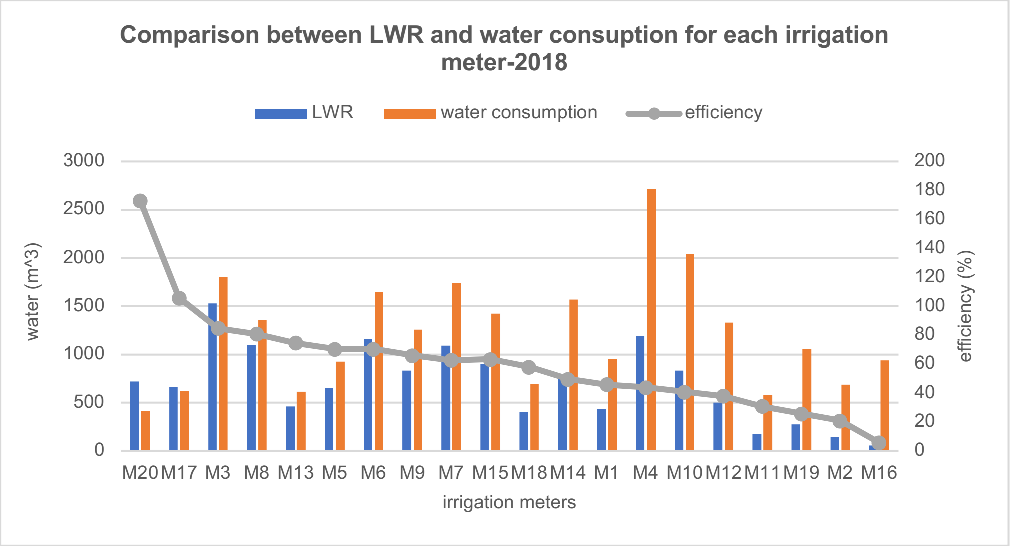


Figure 5-9 Vale do Lobo irrigation efficiency in 2018: comparison between LWR and water consumption at each irrigation meter.

Table 5-10 confirms what was referred above: there is a lower water saving potential in 2018 (5 413.45 €) than in 2017 (7 088.49€), which means less water is being wasted, even though it still is a high number. In terms of irrigation efficiency, there are still 10 irrigation meters associated with areas of inadequate efficiency (marked in red) but in general those efficiencies are higher when compared with 2017. In irrigation meter M3 in 2017 the efficiency was considered satisfactory (61%) and in 2018 it increased to 85% which is an adequate efficiency, although there was a decrease in efficiency in irrigation meter M5, which was 103% and in 2018 decreased to 70%. For the year 2018 the percentages of irrigation meters with inadequate, satisfactory and adequate were the same as 2017, that is 50%, 30% and 20%, respectively.

Table 5-10 Irrigation efficiency associated to each meter (%) and potential water savings (in m^3 and in €) in 2018.

Irrigation meter	Irrigation efficiency (%)	Water savings potential (m^3)	Water savings potential (€)
M1	46	515	257.35 €
M2	21	542	271.07 €
M3	85	274	136.77 €
M4	44	1526	763.17 €
M5	70	274	136.96 €
M6	70	488	243.94 €
M7	63	650	324.99 €
M8	81	260	130.09 €
M9	66	428	214.23 €
M10	41	1 209	604.51 €
M11	31	399	199.36 €
M12	38	827	413.45 €
M13	75	156	77.79 €
M14	49	794	396.80 €
M15	63	521	260.46 €
M16	6	884	441.94 €
M17	106	0	0.00 €
M18	58	292	145.98 €
M19	26	789	394.58 €
M20	173	0	0.00 €
total		10 827	5 413.45 €

A possible explanation to justify the increase in efficiency and the potential of reduction in water savings for the year 2018 is that the precipitation in this year was higher (529 mm) compared with 2017 (317 mm). It was verified that when the precipitation is lower (mostly during summer) excessive water is irrigated to the plants, due to poorly estimation of exact amount of water needs, whereas when it precipitates the amount of water irrigated is commonly zero or close.

5.4.3 Irrigation efficiency in 2019

Once again, LWR was calculated and compared with water consumption for 2019. According to Figure 5-10, the LWR and water consumption curves during the summer period (from May to September) of 2019 are closer than they were in 2017, meaning that irrigation efficiency improved from 2017 to 2019.

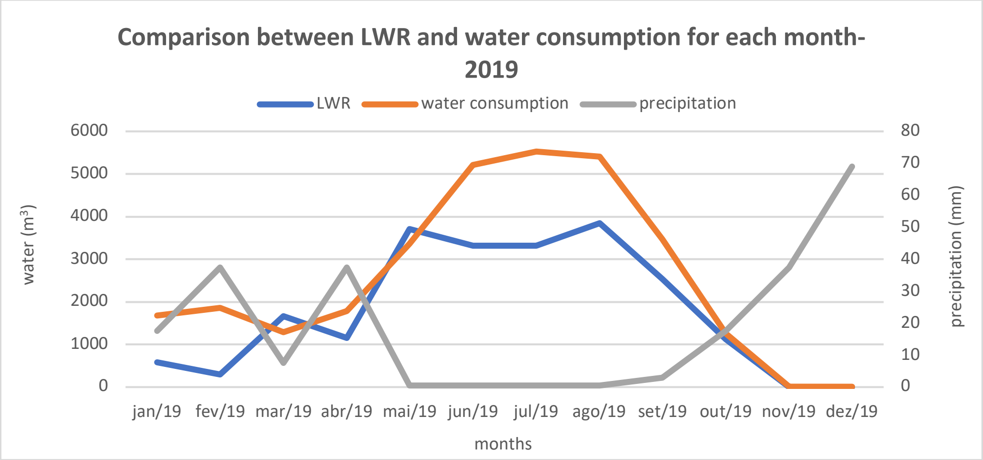


Figure 5-10 Comparison between LWR, water consumption and precipitation in 2019.

Figure 5-11 shows the decreasing efficiencies for all meters. Comparing these results from Figure 5-11 with the years 2017 and 2018 (Figures 5-6 and 5-9, respectively), it is observed a smaller difference between LWR and water consumption among all irrigation meters. The major difference is in M14 in which water consumption (2 992 m^3) was much higher compared with LWR (1 781 m^3).

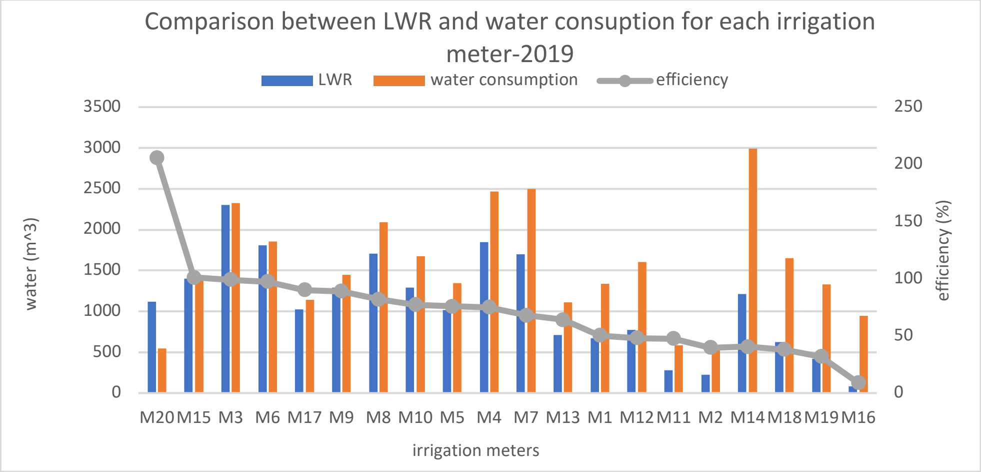


Figure 5-11 Vale do Lobo irrigation efficiency in 2019: comparison between LWR and water consumption at each irrigation meter.

In 2019, the water savings potential was 4 978.99€ (Table 5-11) which is 8% lower than in 2018. In 2019, six irrigation meters were associated with green areas with adequate irrigation efficiencies (marked in green). In this year, 40% of the irrigation meters are associated to areas where irrigation efficiency is inadequate. In the previous years, this percentage was of 50%, meaning that less green areas are suffering from excessive irrigation. Accordingly, the percentage of meters associated to green areas adequately irrigated (marked in green) increased from 20% in 2017 and 2018 to 35% in 2019.

Table 5-11 Irrigation efficiency associated to each meter (%) and potential water savings (in m^3 and in €) in 2019.

Irrigation meter	**Irrigation efficiency (%)**	**Water savings potential (m^3)**	**Water savings potential (€)**
M1	50	664	332.19
M2	40	340	170.22
M3	99	19	9.68
M4	75	619	309.27
M5	76	325	162.64
M6	97	48	24.03
M7	68	797	398.71
M8	82	379	189.33
M9	89	159	79.36
M10	77	384	191.80
M11	47	306	152.85
M12	48	835	417.27
M13	64	398	199.16
M14	40	1781	890.38
M15	101	0	0.00
M16	9	863	431.44
M17	90	113	56.44
M18	38	1025	512.63
M19	32	903	451.58
M20	206	0	0.00
Total		9 958	4 978.99

It is interesting to note that for meters M8, M17 and M20, the irrigation efficiency was always adequate (higher than 80%), that is due to water consumption similar to LWR in the case of the first two irrigation meters (Figures 5-12b,c). In the case of irrigation meter M20 (Figures 5-12a), efficiency is higher than 100% (LWR higher than water consumption), which is not ideal because it can reduce the aesthetics of the turfgrass and of flowerbeds. In these specific cases (Figures 5-12b,c), only M17 and M8 are close to the ideal situation, in which LWR is very similar or equal to the water consumption.

Irrigation meter M16 was the worst in terms of efficiency in 2017, 2018 and 2019. Figure 5-12(d) shows the comparison between LWR and water consumption for M16 during those three years.

The gardens in M16 irrigated area are flowerbeds with considerable small area (in total irrigated area is 98.2 m^2), which in terms of water needs are much lower per square meter when comparing with turfgrass areas.

The year 2019 was when the SIS platform started to operate. In this year, 55% of the irrigation meters had telemetry system implemented, therefore, the decrease in water savings potential might be justified. The upcoming years are crucial to verify this new system accuracy and efficiency.

(a) (b)

(c) (d)

Figure 5-12 Vale do Lobo irrigation efficiency in 2017, 2018 and 2019: LWR versus water consumption for the irrigation meters (a) M20, (b) M17 (c) M8 and (d) M16.

5.4.4 Irrigation efficiency in 2020

In 2020, SIS platform is almost working at 100% in the area of this specific case study: only one irrigation meter does not include telemetry (M2). This year is important to analyse whether the implementation of this system is producing good results in terms of water savings. The controllers have sensors associated with the meteorological station, which will increase or even cease water supply for irrigation, but they do not control the exact amount of water that each green area requires. If there was an algorithm in the controllers, calculating LWR according to meteorological conditions, the exact amount of water needed at a certain time during the day for the irrigation would be the one supplied, achieving the highest efficiency possible.

Due to the timeline of this study it was only approached the months from January until August 2020. Monthly LWR was calculated for this period and compared with monthly water consumption given by the telemetry data, which is presented in Table A-5 in Appendix A. The Figure 5-13 compares, for each irrigation meter, LWR and telemetry from January to August. No telemetry values are available for the irrigation meter M2 due to the reasons explained above.

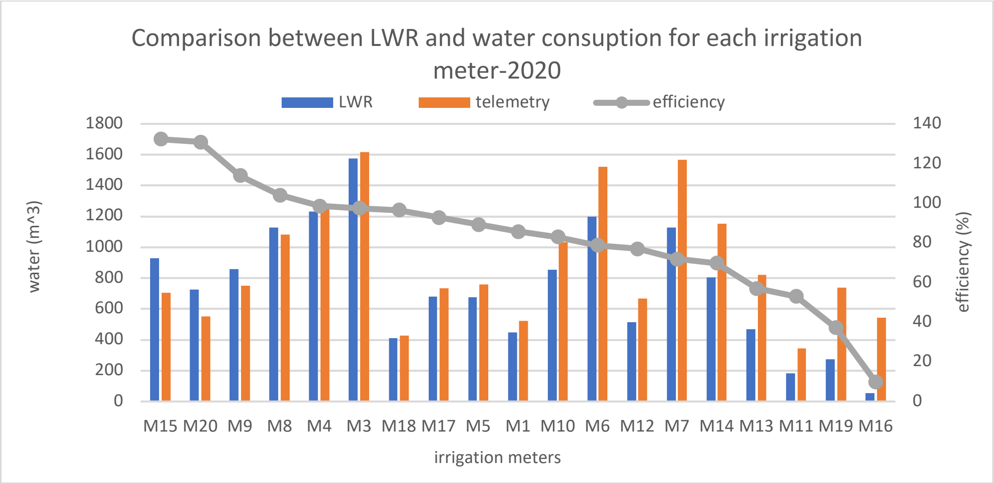


Figure 5-13 Vale do Lobo irrigation efficiency in 2020: comparison between LWR and water consumption at each irrigation meter.

Comparing LWR values with telemetry data for all irrigation meters, it is noticeable an approximation between the water needs and the irrigated volumes, except for the area associated with irrigation meter M16 in which there is still a major difference between these two. According with these results, it seems that, until august 2020, irrigation is being carried out more efficiently, comparing with last years.

Since the data for the year 2020 is not complete, it is not reasonable to compare yearly results from the previous years with 2020. The fairest comparison is to compare the spring/summer period, from May to August, between 2019 and 2020, to assess the irrigation efficiency in the garden before and after SIS was implemented to almost 100%. Figures 5-14(a) and 5-14(b) show the comparison between LWR with water consumption, as given by telemetry, between May and August for the year 2019 and 2020, respectively.

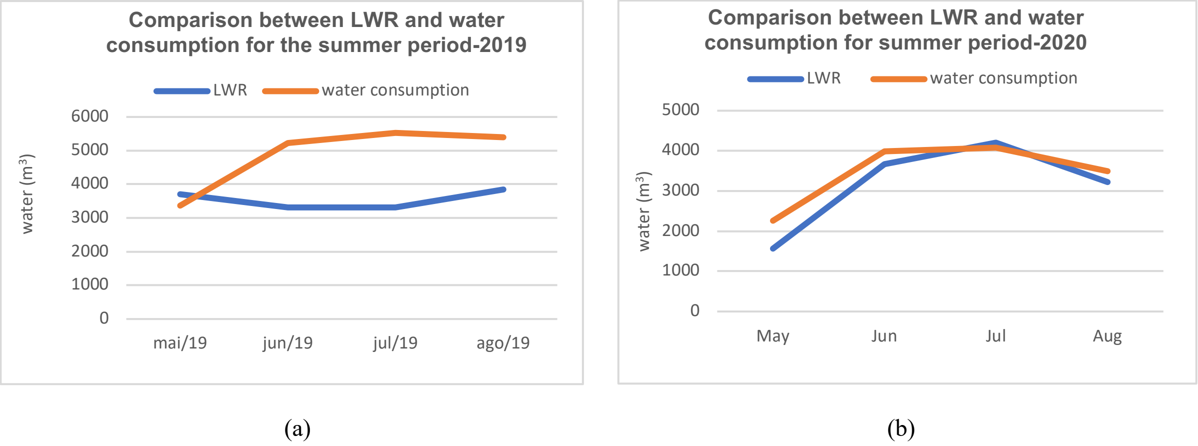


Figure 5-14 Comparison between LWR and water consumption for the summer period in (a) 2019 and (b) 2020.

The consumption profile in 2020 was much more similar to LWR (Figure 5-14b), which is the desired situation to avoid water waste in the irrigation of gardens and landscapes. Table 5-12 resumes irrigation efficiency and water saving potential for years 2019 and 2020 during the summer period (May to August) for all irrigation meters.

Table 5-12 Irrigation efficiency and water savings potential in m^3 and in € for 2019 and 2020 during summer period (may to august) for all irrigation meters.

Irrigation meter	**Irrigation efficiency (%)**		**Water saving potential (m^3)**		**Water savings potential (€)**	
	2019	2020	2019	2020	2019	2020
M1	50	90	495	55	247.53	27.23
M2	80	-	40	-	20,.5	-
M3	100	110	22	0	10.90	0.00
M4	80	110	296	0	147.98	0.00
M5	80	90	211	34	105.36	16.79
M6	80	80	242	231	121.22	115.29
M7	70	80	451	298	225.65	149.25
M8	90	110	96	0	47.78	0.00
M9	90	120	81	0	40.64	0.00
M10	80	90	221	75	110.42	37.47
M11	50	60	205	120	102.45	60.00
M12	40	80	643	89	321.71	44.26
M13	70	60	197	274	98.52	137.04
M14	40	80	1248	179	623.88	89.61
M15	90	140	104	0	51.18	0.00
M16	10	10	688	414	343.98	207.06
M17	100	90	0	32	0.00	15.98
M18	50	120	348	0	173.80	0.00
M19	50	40	338	396	169.15	197.82
M20	430	140	0	0	0.00	0.00
Total			5 926	2 196	2 962.95	1 098.10

Analysing irrigation efficiency between meters, there was as increase in all the meters (represented in green are all efficiencies equal or above 80%, in yellow between 60% and 80% and in red bellow 60%), except in M17 and M19. Optimal efficiency is equal to 100%, even thought there was an increase in almost all meters ,there are some with efficiencies slightly above 100% (M3, M4, M8, M9, M15, M18, M20), which means theses gardens are being irrigated less than their theoretical water needs (as mentioned above water stress will reduce aesthetics of the gardens) or that these differences are due to uncertainties in collected data. In meter M20, in 2019, the efficiency is significantly higher than 100% (430%) and, in 2020, it decreased to 140% which is closer to 100%, which demonstrates an improvement on the efficiency index of the meter.

The increase in efficiency resulted in a lower water saving potential in summer 2020 (2 196 m^3) compared with 2019 (5 926 m^3), corresponding to a decrease of 37%. In summer 2020 the water saving potential was 1 098.10€, lower than 2 962.95€ calculated for summer 2019. These numbers results obtained previously, that, in 2020, the water is being used more efficiently compared with 2019. In 2020 40% of the irrigation meters are efficient (efficiency between 80% and 100%), 10% are satisfactory, 10% inadequate and the remaining meters represent efficiencies above100%.

Figure 5-15 compares the efficiencies of all irrigation meters between 2017 and 2020 to allow a more complete understanding of increase in efficiency throughout the years: 75% of all irrigation meters are more efficient in 2020 than in previous years.

It is important to refer that, in 2020, there are indeed water savings, very much likely due to the implementation of the “Smart Irrigation System”, but this study does not access increase in energy use and the respective increase in costs related with more energy use, which is connected with all the new electrical devices that require energy to function (i.e., telemetry, controllers).

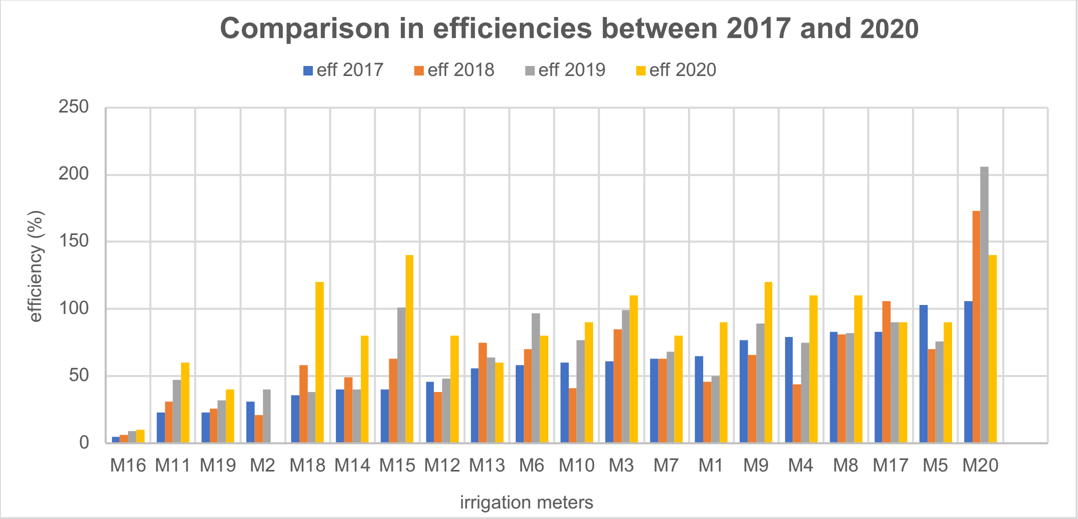


Figure 5-15 Comparison between 2017 and 2020 for all irrigation meters.

5.5 Application of the proposed energy balance

The methodology proposed for the energy balance in 3.3 for urban irrigation systems was applied in Vale do Lobo case study, for the years 2017, 2018 and 2019. A top-down approach was carried out. Not all the components of the energy balance can be calculated, because some of them, as explained, require mathematical modelling, and there was no mathematical model available to analyse this system. It was possible to calculate the total system input energy, the minimum required energy and the energy associated with water losses, data used for all irrigation meters can be consulted in Table A-7 in the Appendix A.

5.5.1 Total system input energy

In order to calculate the total system input volume, Equations 6 and 7 were used. Figure 5-2 shows the spatial distribution of the 20 different water meters in Vale do Lobo case study. Irrigation meter M16 is located at the inlet of the irrigation system (Z_e) and irrigation meter M1 is located at the minimum elevation of this irrigation system (Z_{min}). Pressure head at the inlet of the system, $P_{entrance}/\gamma$, is 35 m, value provided by Infralobo. Table 5-13 bellow summarizes the values used to calculate pressure head applied in the irrigation system.

Table 5-13 Node elevation at the entrance, pressure head at the entrance and minimum node elevation of Vale do Lobo irrigation system.

Z_e (m)	**$P_{entrance}$ (m)**	**Z_{min} (m)**
32	35	22

After calculating pressure head applied in the irrigation system, Equation 6 was used in order to obtain the total system input energy for the three years of 2017, 2018 and 2019. These values can be found in Table 5-14.

Table 5-14 Total system input energy for the years 2017, 2018 and 2019.

Total system input energy (kWh/year)		
2017	**2018**	**2019**
3 863	2 983	3 785

5.5.2 Minimum required energy for irrigation

The minimum required energy for irrigation was calculated using Equations 8 and 9. The minimum required energy for other uses was not calculated because there are no other uses associated in this case study. Existing sprinklers are of Rain Bird, series 5000, with a minimum working pressure head, P_{min}/γ, of 17 m. The elevation of all the 20 water meters was determined, using Google Earths 2020 and the minimum elevation of the system was established, Z_{min}=22 m. Lastly, Equation 9 was used for calculating the minimum required energy for the years 2017, 2018 and 2019 (Table 5-15).

Table 5-15 Minimum required energy for irrigation in the years 2017, 2018 and 2019.

Minimum required energy for irrigation (kWh/year)		
2017	**2018**	**2019**
1 281	1 018	1 582

5.5.3 Energy associated with water losses

The energy associated with water losses is proportional to the water losses percentage from the previously estimated water balance. Using Equation 10, the energy associated with water losses for the years 2017, 2018 and 2019 was estimated (Table 5-16).

Table 5-16 Energy associated with water losses for the years 2017, 2018 and 2019.

Energy associated with water losses (kWh)		
2017	**2018**	**2019**
1 727	1 285	1 148

The energy associated with water losses is undesirable in any water supply system and should be as low as possible. An efficient irrigation system is the one that saves both water and its embedded energy (Mamade et al., 2018). The amount of energy associated with water losses has been reducing from 2017 to 2019, which is expected since the percentage of water losses has also dropped in those years (Table 5-4). Reducing water losses not only has a positive impact on the amount of water saved but also on the amount of energy saved. Efficient irrigation systems reduce both water and energy consumption, which will directly decrease the costs related with water and energy use.

5.5.4 Energy performance indicators

The energy balances were calculated for the years 2017, 2018 and 2019 (Tables 5-17, 5-18 and 5-19). Highlighted in light blue are the energy balance components that could be computed using the top-down approach and in white the components that can only be obtained by using a more detailed bottom-up approach and that could not be calculated.

Table 5-17 Energy balance for the year 2017 for Vale do Lobo irrigation system (kWh).

Natural input energy (E_N) Shaft input energy (E_S)	Total system input energy (E_{INP}) 3 863	Energy associated with effective use (E_{EU}) 2 125 (55%)	Energy associated with water supplied to consumers (E_{SUP})	Minimum required energy for irrigation (E_{MIN}) 1 281
				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}) 1 727 (45%)		

Table 5-18 Energy balance for the year 2018 for Vale do Lobo irrigation system (kWh).

<table>
<tr><td rowspan="7">Natural input energy (E_N)
Shaft input energy (E_S)</td><td rowspan="7">Total system input energy (E_{INP}) 2 983</td><td rowspan="6">Energy associated with effective use (E_{EU}) 1 700(57%)</td><td rowspan="3">Energy associated with water supplied to consumers (E_{SUP})</td><td>Minimum required energy for irrigation (E_{MIN}) 1 018</td></tr>
<tr><td>Minimum required energy for other uses ($E_{MIN,o}$) 0</td></tr>
<tr><td>Surplus energy (E_{SUR})</td></tr>
<tr><td rowspan="3">Dissipated energy (E_{DIS})</td><td>Pipe friction ($E_{diss,f}$)</td></tr>
<tr><td>Valve head losses ($E_{diss,v}$)</td></tr>
<tr><td>Pumping stations' inefficiency ($E_{diss,P}$) (-)</td></tr>
<tr><td colspan="3">Energy associated with water losses (E_{WL}) 1 285 (43%)</td></tr>
</table>

Table 5-19 Energy balance for the year 2019 for Vale do Lobo irrigation system (kWh).

<table>
<tr><td rowspan="7">Natural input energy (E_N)
Shaft input energy (E_S)</td><td rowspan="7">Total system input energy (E_{INP}) 3 785</td><td rowspan="6">Energy associated with effective use (E_{EU}) 2 649 (70%)</td><td rowspan="3">Energy associated with water supplied to consumers (E_{SUP})</td><td>Minimum required energy for irrigation (E_{MIN}) 1 582</td></tr>
<tr><td>Minimum required energy for other uses ($E_{MIN,o}$) 0</td></tr>
<tr><td>Surplus energy (E_{SUR})</td></tr>
<tr><td rowspan="3">Dissipated energy (E_{DIS})</td><td>Pipe friction ($E_{diss,f}$)</td></tr>
<tr><td>Valve head losses ($E_{diss,v}$)</td></tr>
<tr><td>Pumping stations' inefficiency ($E_{diss,P}$) (-)</td></tr>
<tr><td colspan="3">Energy associated with water losses (E_{WL}) 1 148 (30%)</td></tr>
</table>

Based on the energy balances for this irrigation system, the three energy performance indicators referred in 3.3.5 were calculated in order to assess the energy efficiency of this system from 2017 to 2019.

Figure 5-16 compares the three energy performance indicators during the three years (2017, 2018 and 2019) in which the energy balance and water balance were 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 5.4 this was expected, due to the decrease in water losses, which is directly connected with energy use.

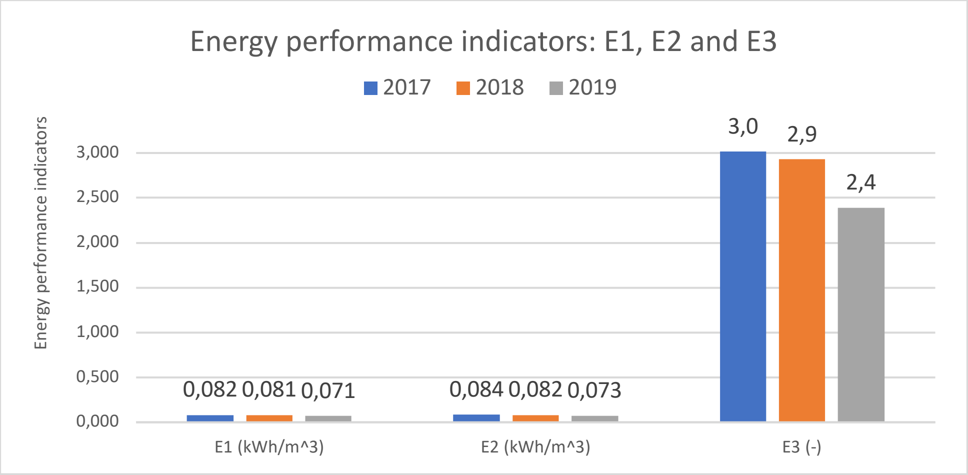


Figure 5-16 Energy performance indicators for Vale do Lobo.

Comparing the Vale do Lobo energy performance indicators with reference values for water supply systems (Mamade, 2014), E3 has a fair performance for the three years (between two and four), which means energy supplied to the system is almost three times the minimum required energy.

5.6 Future improvements

Irrigation efficiency in Vale do Lobo gardens has been improving in the last three years, although there are still some improvements to be made. In general irrigation is adequately carried out, as it is lower during rainy period (autumn/winter), increasing in warmer and drier periods (spring/summer) to meet plants water needs. Future improvements include:

- To further investigate the reasons underlying the lowest irrigation efficiencies (lower than 60%);
- To understand the problem with irrigation meter M20, which associated green space is apparently suffering inappropriate irrigation and water stress;
- To solve problem of irrigation meter M16, which is the one with the lowest efficiency;
- To include an algorithm in the irrigation controller for estimating daily LWR, in order to better adapt the irrigation volumes to weather conditions;
- To develop a hydraulic model of the irrigation system network in order to be able to calculate the energy balance using the bottom-up approach;
- To explore how the dissipated and surplus energy could be recovered for other uses.

6 CASE STUDY 3: MARECHAL CARMONA URBAN PARK

6.1 Introduction

In the present chapter, the last case study is presented, Parque Marechal Carmona in Cascais. In a recent study (Covas et al., 2019) ,this park was identified as a large water consumer (39 000 m^3/year), having a high water saving potential. The proposed water balance was applied for this park in the years 2015, 2016 and 2017. Several performance indicators were calculated and future improvements are proposed.

6.2 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 water network within the park supplies water 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 in total five water meters in the park that measure all water consumptions in the park. Figure 6-1 illustrates Marechal Carmona garden and several of the different landscapes.

Figure 6-1 Examples of landscaping characteristics in Marechal Carmona park.

6.3 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 was calculated using the proposed approach (Tables 6-1 to 6-3), the water consumption for all the meters existent in the park for all the three studied years can be consulted in Tables B-1,2 and 3 in Appendix B. The subcomponents that could be calculated are presented in light blue.

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 engineers that manage the park. Results show that system input volume values are more or less constant for the three years.

Consumption for irrigation, LWR, was calculated for the three years following the methodology described in 3.2.3. The monthly data for the evapotranspiration and precipitation was extracted from Instituto Português do Mar e da Atmosfera (IPMA), these values can be consulted in Table B-4 in Appendix B, and the coefficients DU_{LQ} and K_L used in the equation to calculate LWR were the same used in Table 5-2.

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 was considered that from November to February there is no irrigation, due to precipitation (see Figure 6-2) 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, it was considered as constant in every month throughout the year. Ideally, consumption for other uses would be measured by a dedicated meter.

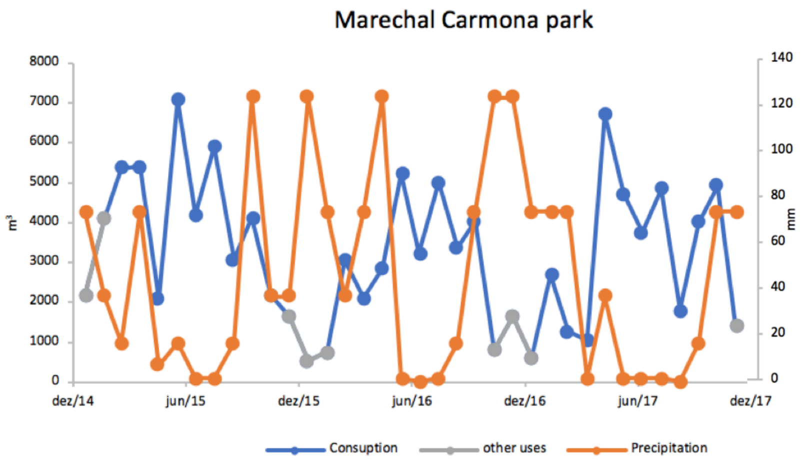


Figure 6-2 Water consumption of Marechal Carmona park from 2015 to 2017.

The pattern in Figure 6-2 shows that water consumption is much lower in winter, because there is no need to irrigate, while the opposite happens during the summer months.

The methodology to calculate water losses was the same as in the previous case study (5.3.3). Irrigation losses and network real losses were coupled, because it was not possible to calculate them separately. Apparent losses were 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).

Table 6-1 Water balance for the year 2015 for Marechal Carmona.

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 (-)

Table 6-2 Water balance for the year 2016 for Marechal Carmona.

System input volume 33953 m^3 (10 186 m^3 Network supply and 23 767 m^3 Underground sources)	Effective use 30 955 m^3 (90 %)	Consumption for irrigation 15 854 m^3 (50 %)	Irrigation needs 15 854 m^3 (50 %)
		Consumption for other uses 15 101 m^3 (40%)	wc's, restaurant, drinking fountains and lakes filling
	Water losses 2 998 m^3 (10%)	Apparent losses 679 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 679 m^3 (2%)
		Irrigation losses & Network real losses 2 319 m^3 (8%)	Evaporation losses, deep percolation to the soil layers and runoff
			Leakage in the irrigation network
			Losses in canals and in intermediate tanks (-)

Table 6-3 Water balance for the year 2017 for Marechal Carmona.

System input volume 40066 m^3 (12 020 m^3 Network supply and 28 046 m^3 Underground sources)	Effective use 13 0955 m^3 (88 %)	Consumption for irrigation 17 251 m^3 (43%)	Irrigation needs 17 251 m^3 (43%)
		Consumption for other uses 18 149 m^3 (45%)	wc's, restaurant, drinking fountains and lakes filling
	Water losses 4 675 m^3 (12%)	Apparent losses 801 m^3 (2%)	Unauthorised consumption 0 m^3
			Metering inaccuracies 801 m^3 (2%)
		Irrigation losses & Network real losses 3 874 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 (-)

The percentages of the effective water use and of water losses are presented in Table 6-4. Effective use corresponds to the percentage of water that was effectively used both for irrigation and consumption by other uses. In the three years this percentage 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 was compared with the water consumed for irrigation and the irrigation efficiency was calculated (Table 6-5). The results show that the irrigation efficiency was satisfactory in 2015 and 2017 ($60 \leq IE < 80\%$) and adequate in 2016 ($IE \geq 80\%$).

Table 6-4 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 6-5 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

6.4 Future improvements

The application of the water balance to Marechal Carmona urban park suggests that water management in the park is efficient, as the water losses are low and the irrigation efficiency is high. However, the results of the water balance have a high uncertainty in the estimation of the components. On the other hand, the water consumption for other uses is very high and the efficiency of such uses should also be investigated. Further studies should focus on:

- the assessment of the irrigated areas associated with each irrigation meter, for a better understanding of the efficiency associated with each one;
- the adequate assessment of network real losses by running field tests to measure leakage during the night, when no irrigation or other uses are consuming water;
- the adequate assessment of consumption for other uses, by measuring them when no irrigation is taking place or by separating the two networks;
- flow meters should be installed to measure the abstracted groundwater to better estimate the system input volume;
- a detailed hydraulic model of the irrigation system network of Marechal Carmona park should be developed in order to calculated the complete energy balance.

Without this fieldwork it is very difficult to further promote water and energy efficiency measures. Irrigation efficiency can only be more accurately evaluated after the fieldwork is carried out. Furthermore, the time and frequency of the irrigation can be further optimized by considering local weather conditions.

7 CASE STUDIES COMPARISON

Three different gardens were studied in this thesis. The first one is an historical garden, the second one a modern urban garden comprising green areas close to a residential area (the most recent of the three) and the last one, an urban park where many recreational activities take place. To better compare these three gardens their yearly water consumption was calculated (Table 7-1).

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

Table 7-1 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 where water is mostly consumed for irrigation, as well as for other purposes (cafés, wc's, lakes filling, etc). This study should be extended to other case studies including gardens with different specificities, to conclude if historical gardens consume less water when comparing with the modern ones.

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 for irrigation, contrary to Marechal Carmona urban park, which might be two reason that justify the lower water consumption.

Table 7-1 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

The city of Madrid set goals for yearly water consumption of their gardens per square meter of 0.25 $m^3.m^{-2}.year^{-1}$ (Sostenibilidad, 2005). This is a very ambitious goal. Both Vale do Lobo and Cascais gardens are currently consuming much more water than the set goal for Madrid. This might indicate that there are still some improvements to be done in terms of water consumption in these two urban gardens.

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.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Main conclusions

A methodology to calculate water and energy balances for gardens was 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 smart irrigation system) and Marechal Carmona urban park (garden with traditional irrigation system and recreational uses). The proposed balances were based on the existing balances for the urban water supply systems and for collective irrigation systems to which some changes were introduce to better tailor these balances for the water and energy uses in the gardens.

In the water balance, authorized consumption was substituted 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 (e.g., restaurants, fountains, lakes filling). 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 was 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 show that the historical garden is much more efficient than the modern urban garden of Vale do Lobo.

8.2 Recommendations for future works

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

- To further test the proposed water balance methodology in other gardens, including gardens where different water uses.
- 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 for each garden category to allow a fairer comparison.

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APPENDIX A

Table A-1 Vale do Lobo garden characteristics: meter, type of vegetation and area.

Meter	Type of vegetation	Area (m^2)	Meter	Type of vegetation	Area (m^2)	Meter	Type of vegetation	Area (m^2)
M1	flowerbed	16.655	**M8**	turfgrass	709.422	**M14**	turfgrass	544.735
	flowerbed	41.347		flowerbed	86.354		turfgrass	219.211
	flowerbed	10.517		flowerbed	17.6		turfgrass	73.312
	flowerbed	50.301		flowerbed	14.561		turfgrass	16.825
	flowerbed	105.991		flowerbed	204.789		turfgrass	118.121
	turfgrass	397.328		flowerbed	23.844		flowerbed	22.484
M2	flowerbed	168.763		flowerbed	20.8	**M15**	turfgrass	1142.235
	flowerbed	40.799		flowerbed	47.969	**M16**	flowerbed	11.07
	flowerbed	13.826		flowerbed	6.65		flowerbed	55.356
	flowerbed	40.818		turfgrass	383.326		flowerbed	15.742
M3	turfgrass	1046.198		flowerbed	13.343		flowerbed	6.023
	turfgrass	74.735	**M9**	turfgrass	1052.622		flowerbed	5.357
	turfgrass	31.794	**M10**	turfgrass	108.675		flowerbed	2.359
	flowerbed	16.412		turfgrass	24.061		flowerbed	2.337
	flowerbed	28.498		turfgrass	17.067	**M17**	turfgrass	211.941
	flowerbed	13.272		turfgrass	95.183		turfgrass	141.511
	turfgrass	608.789		turfgrass	56.087		flowerbed	21.041
	flowerbed	136.081		turfgrass	750.835		turfgrass	61.03
	turfgrass	3.017	**M11**	turfgrass	59.231		flowerbed	31.239
	flowerbed	63.837		turfgrass	166		turfgrass	43.402
M4	turfgrass	506.347	**M12**	flowerbed	39.086		flowerbed	19.695
	turfgrass	94.483		flowerbed	35.622		flowerbed	4.126
	turfgrass	109.853		flowerbed	13,243		flowerbed	7.131
	flowerbed	34.77		flowerbed	5,.09		flowerbed	76.65
	turfgrass	58.284		flowerbed	31.963		turfgrass	267.488
	flowerbed	128.587		flowerbed	42.128	**M18**	turfgrass	283.454
	flowerbed	88.511		flowerbed	40.177		flowerbed	41.876
	turfgrass	7.62		flowerbed	21.554		flowerbed	22.718
	flowerbed	26.942		flowerbed	35.921		flowerbed	30.084
	flowerbed	30.096		flowerbed	10.912		flowerbed	94.323
	turfgrass	518.804		flowerbed	18.196		flowerbed	141.926
M5	turfgrass	482.254		flowerbed	55.221	**M19**	flowerbed	66.91
	flowerbed	15.922		flowerbed	3.996		flowerbed	34.366
	flowerbed	28.276		flowerbed	13.025		flowerbed	26.724
	flowerbed	58.512		flowerbed	21.174		flowerbed	12.51
	flowerbed	16.17		flowerbed	23.411		flowerbed	28.148
	turfgrass	37.499		turfgrass	291.631		flowerbed	10.941
	flowerbed	17.328		turfgrass	36.531		flowerbed	8.796
	flowerbed	10		flowerbed	39.549		flowerbed	29.848
	flowerbed	17.633	**M13**	flowerbed	170.696		flowerbed	4.457
	flowerbed	60.856		turfgrass	63.282		flowerbed	4.063
	turfgrass	134.304		flowerbed	16.917		flowerbed	3.887
	turfgrass	21.389		flowerbed	12.156		flowerbed	5.569
M6	turfgrass	1381.519		turfgrass	49.139		flowerbed	6.31
	turfgrass	43.729		flowerbed	36.617		flowerbed	18.483
	turfgrass	46.107		flowerbed	74.523		flowerbed	13.087
M7	turfgrass	684.506		turfgrass	197.155		flowerbed	1.564
	turfgrass	148.187		flowerbed	82.536		flowerbed	73.3
	turfgrass	102.961					flowerbed	151.944
	flowerbed	61.713				**M20**	flowerbed	150.258
	turfgrass	31.045					flowerbed	217.719
	turfgrass	378.268					flowerbed	926.18
							flowerbed	5.234
							flowerbed	25.488

Table A-2 Vale do Lobo water consumption in the year 2017 (m^3).

Meter	jan	feb	mar	apr	may	jun	jul	ago	sep	oct	nov	dec	Total
M1	0	0	0	0	0	35	150	500	50	86	29	1	851
M2	0	0	0	0	0	85	135	120	45	186	20	1	592
M3	210	0	0	195	230	380	615	600	270	331	32	143	3006
M4	2	0	0	4	34	65	615	535	245	335	55	0	1890
M5	5	0	0	5	0	0	340	195	75	106	78	0	804
M6	22	0	0	173	200	590	530	450	230	276	37	0	2508
M7	455	0	0	0	130	25	880	425	210	47	1	0	2173
M8	15	0	0	65	85	255	540	330	140	172	67	0	1669
M9	32	3	0	100	115	195	305	290	155	158	0	0	1353
M10	27	0	0	138	145	230	435	485	135	109	32	0	1736
M11	18	0	0	100	70	130	235	275	75	63	22	0	988
M12	40	0	0	130	150	175	265	298	147	120	42	0	1367
M13	15	15	35	105	95	150	225	195	90	60	54	0	1039
M14	40	25	90	270	230	345	537	453	200	168	56	9	2423
M15	119	0	240	310	290	370	360	385	315	244	175	1	2809
M16	85	0	0	135	255	195	220	180	210	155	57	28	1520
M17	20	15	45	80	90	150	215	185	90	81	28	0	999
M18	42	0	143	195	160	190	185	185	165	131	42	0	1438
M19	50	105	85	185	135	175	195	245	170	108	46	0	1499
M20	35	10	70	110	220	0	80	100	90	118	36	0	869
Total	1232	173	708	2300	2634	3740	7062	6431	3107	3054	909	183	31533

Table A-3 Vale do Lobo water consumption in the year 2018 (m^3).

Meter	jan	feb	mar	apr	may	jun	jul	ago	sep	oct	nov	dec	Total
M1	0	26	0	0	58	0	198	132	285	250	0	0	949
M2	0	20	0	0	13	0	236	38	105	172	65	36	685
M3	1	27	0	36	193	0	640	499	187	219	0	0	1802
M4	5	99	10	0	640	435	527	488	215	294	0	0	2713
M5	0	22	0	15	85	142	218	134	170	141	0	0	927
M6	1	0	1	20	98	262	433	423	177	231	0	0	1646
M7	0	1	1	25	114	465	473	183	320	0	160	0	1742
M8	0	71	2	17	110	196	301	374	177	108	0	0	1356
M9	0	0	0	6	118	225	369	290	116	133	0	0	1257
M10	1	45	0	23	5	123	72	960	123	350	335	0	2037
M11	0	32	0	7	0	0	51	304	71	110	1	0	576
M12	0	52	11	32	0	0	48	720	153	227	86	0	1329
M13	1	23	0	4	48	0	60	180	90	206	0	0	612
M14	0	26	0	16	251	190	308	258	93	355	0	74	1571
M15	0	0	0	9	190	223	30	14	73	881	0	0	1420
M16	0	0	0	0	30	33	237	462	175	0	0	0	937
M17	1	50	5	10	0	25	30	374	49	78	0	0	622
M18	0	49	0	12	71	20	50	70	317	105	0	0	694
M19	0	56	55	20	100	50	40	552	164	23	0	0	1060
M20	0	26	6	24	0	20	10	253	75	-	0	0	414
Total	10	625	91	276	2124	2409	4331	6708	3135	3883	647	110	24349

Table A 4 Vale do Lobo water consumption in the year 2019 (m^3).

Meter	jan	feb	mar	apr	may	jun	jul	ago	sep	oct	nov	dec	Total
M1	81	62	41	52	55	318	299	269	161	0	0	0	1338
M2	50	49	49	48	36	46	52	57	132	45	0	0	564
M3	138	147	143	143	311	365	449	455	160	14	0	0	2325
M4	126	158	111	138	283	355	437	433	307	117	4	0	2469
M5	61	57	44	52	150	247	240	242	180	71	0	0	1344
M6	112	124	85	113	268	407	391	353	0	0	0	0	1853
M7	115	121	88	115	287	435	428	412	344	154	0	0	2499
M8	111	315	0	107	254	334	314	316	238	99	0	0	2088
M9	76	82	54	72	177	255	248	243	177	66	0	0	1450
M10	73	81	56	75	193	297	291	281	230	97	0	0	1674
M11	22	24	18	20	84	107	101	93	81	32	0	0	582
M12	53	51	68	52	209	314	312	328	166	55	0	0	1608
M13	57	54	45	34	105	183	189	192	170	82	0	0	1111
M14	129	115	90	110	416	545	583	494	375	135	0	0	2992
M15	0	0	78	293	280	279	273	185	0	0	0	0	1388
M16	0	55	0	0	0	122	301	321	135	12	0	0	946
M17	66	63	43	59	57	177	203	216	181	73	0	0	1138
M18	170	159	140	156	103	203	216	241	187	78	0	0	1653
M19	175	89	78	95	66	186	147	225	191	75	0	0	1327
M20	65	61	60	48	33	44	53	46	58	59	9	9	545
Total	1680	1867	1291	1782	3367	5219	5527	5402	3473	1264	13	9	30894

Table A-5 Telemetry data for Vale do Lobo in the year 2020 until august (m^3).

Meter	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Total
M1	0	4	56	10	64	121	136	130	521
M2	-	-	-	-	-	-	-	-	0
M3	0	93	184	28	211	326	401	373	1616
M4	5	77	135	24	166	251	315	276	1249
M5	0	42	75	11	102	161	201	166	758
M6	-	7	138	20	167	560	300	264	1456
M7	0	88	160	23	199	338	407	355	1570
M8	0	70	114	21	147	215	284	233	1084
M9	0	45	86	12	105	152	193	159	752
M10	0	60	115	23	156	222	272	183	1031
M11	0	19	37	7	47	76	85	75	346
M12	0	39	73	10	90	133	169	153	667
M13	0	42	75	14	101	176	229	183	820
M14	0	86	153	21	193	220	290	188	1151
M15	0	16	92	21	128	150	155	142	704
M16	0	81	0	0	52	121	153	137	544
M17	0	11	73	16	102	183	174	174	733
M18	0	3	68	14	83	94	66	66	394
M19	0	40	49	9	88	276	143	133	738
M20	0	17	4	17	58	208	108	103	515
Total	5	840	1687	301	2259	3983	4081	3493	16649

Table A-6 Meteorological conditions in 2017, 2018, 2019 and until august 2020 in the area of Vale do Lobo.

	Precipitation (mm)				Evapotranspiration (mm)			
	2017	**2018**	**2019**	**2020**	**2017**	**2018**	**2019**	**2020**
Jan	37.5	37.5	17.5	37.5	60	57.5	17.5	37.5
Feb	75	75	37.5	3	60	67.5	37.5	3
Mar	75	125	7.5	75	95	77.5	7.5	75
Apr	17.5	75	37.5	119.2	125	95	37.5	119.2
May	27.5	17.5	0.5	66	147.5	147.5	0.5	66
Jun	0.5	37.5	0.5	3.4	185	160	0.5	3.4
Jul	0.5	0.5	0.5	0	192.5	192.5	0.5	0
Aug	0.5	0.5	0.5	0	187.5	217.5	0.5	0
Sep	0.5	3	3		150	125	3	
Oct	7.5	75	17,5		95	85	17.5	
Nov	37.5	75	37.5		77.5	47.5	37.5	
Dec	37.5	7.5	69		67.5	47.5	69	

Table A-7 Meter elevation (Z), minimum pressure head (H_{min}) and minimum required energy (E_{min}).

Meters	Z (m)	Hmin (m)	Emin 2017 (kWh)	Emin 2018 (kWh)	Emin 2019 (kWh)
M1	22	17	25.50	20.10	31.17
M2	27	22	11.03	8.56	13.39
M3	31	26	129.23	108.18	163.19
M4	33	28	114.37	90.45	141.05
M5	33	28	63.02	49.78	77.65
M6	32	27	107.29	85.12	132.66
M7	33	28	104.99	83.24	129.70
M8	33	28	105.80	83.53	130.29
M9	32	27	76.76	60.90	94.91
M10	30	25	71.02	56.35	87.82
M11	31	26	15.82	12.55	19.56
M12	33	28	47.98	38.27	58.95
M13	33	28	44.32	34.79	54.32
M14	33	28	74.71	59.25	92.32
M15	32	27	83.29	66.08	102.99
M16	32	27	5.03	3.90	6.11
M17	33	28	63.35	50.11	78.14
M18	33	28	39.02	30.65	47.85
M19	32	27	25.67	19.91	31.15
M20	34	29	72.92	56.55	88.50

APPENDIX B

Table B-1 Marechal Carmona park water consumption in the year 2015 (m^3).

Meter	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Total
M1	0	30	0	32	0	15	0	17	0	18	0	7	119
M2	0	1017	0	561	0	2470	0	1156	0	1175	0	1213	6417
M3	0	357	0	945	0	616	0	774	0	790	0	549	4031
M4	898	961	1354	786	532	601	784	767	732	776	756	0	8947
M5	1259	1742	4015	3088	1560	3373	3418	3197	2361	1375	1447	0	26835
Total	2157	4107	5369	5412	2092	7075	4202	5911	3093	4134	2203	1769	47524

Table B-2 Marechal Carmona park water consumption in the year 2016 (m^3).

Meter	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Total
M1	0	14	0	1	0	7	0	6	0	18	0	12	58
M2	0	0	0	0	0	1311	0	680	0	752	0	740	3483
M3	0	720	0	17	0	383	0	445	0	850	0	618	3033
M4	346	353	391	391	1087	1295	907	914	838	290	1	0	6813
M5	210	920	2662	1711	1750	2230	2333	2962	2544	2143	802	298	20565
Total	556	2007	3053	2120	2837	5226	3240	5007	3382	4053	803	1668	33952

Table B-3 Marechal Carmona park water consumption in the year 2017 (m^3).

Meter	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	Oct	Nov	Dec	Total
M1	0	12	0	15	0	14	0	14	0	14	0	14	83
M2	0	744	0	0	0	9	0	128	0	334	0	174	1389
M3	0	1338	0	178	0	432	0	704	0	726	0	598	3976
M4	0	0	0	584	4690	1592	840	751	0	1048	2991	0	11656
M5	635	604	1271	2133	2026	2589	2926	3242	2138	1887	1929	657	19111
Total	635	2698	1271	2910	6716	4636	3766	4839	2138	4009	4920	1443	36215

Table B-4 Meteorological conditions in 2015, 2016 and 2017 in the area of Cascais.

	Precipitation (mm)			Evapotranspiration (mm)		
	2015	2016	2017	2015	2016	2017
jan	75	125	75	40	42.5	48.5
feb	37.5	75	75	47.5	67.5	55
mar	17.5	37.5	75	85	75	62.5
Apr	75	75	37.5	85	85	105
May	7.5	125	105	137.5	115	105
Jun	17.5	2	2	135	147.5	135
Jul	2	0.5	2	142.5	160	139
Aug	2	2	2.5	147.5	147.5	140
Sep	17.5	17.5	0.5	105	115	107
Oct	125	75	17,5	75	85	95
Nov	37.5	75	75	77.5	47.5	55
dec	37.5	7.5	75	67.5	47.5	42.5