Design of a Bioretention System with Water Reuse for Urban Agriculture through a Daily Water Balance

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Abstract: The present work proposes the use of green infrastructure (GI) called sustainable urban agriculture drainage systems with water reuse (SUADS-WR) to manage percolated water sustainably in urban agricultural areas (f.i. golf courses). The substrate of the system is commonly used in golf courses and includes a subsurface reservoir for water that exceeds the edaphic zone. Data obtained from a lysimeter, installed in a golf course in Spain, are used to validate the methods employed in developing hydro-informatics tools based on daily water balance, which estimates the water requirement for crops, reservoir height, and capacity for unused water reuse. Reference evapotranspiration can be estimated using the Penman–Monteith or Hargreaves–Samani method. The results were compared with experimental data, revealing that the estimated irrigation depths were lower than the supplied ones and that the estimated percolation was consistent with the measured field drainage. The applicability of the proposed methods for determining the reservoir height and irrigation depth for any type of crop in urban agricultural areas is confirmed. With the implementation of SUADS-WR, the harvested water depth can cover more than 38% of the annual water demand for the crop and utilize leached fertilizers, thus preventing pollution of the receiving surface water body or groundwater.

Keywords: nature-based solutions; urban water-harvesting infrastructure; golf course watering; evapotranspiration; stormwater reuse; urban resilience; prevention of urban pollution

1. Introduction

Nowadays, worldwide, more than 255 million people reside in urban areas facing extreme high water stress conditions, and by the year 2030, it is estimated that this number will exceed 470 million inhabitants [1]. It is expected that large cities will face increased water stress due to continuous economic and demographic growth, as well as the occurrence of more severe extreme weather events, including heatwaves and droughts. In fact, the loss of green spaces associated with urbanization growth is linked to the development of urban heat islands, which manifest by increasing the frequency and intensity of heatwaves. Additionally, cities with less vegetation and surface water bodies exacerbate the effects of climate change in urban environments compared to the effects in rural areas [2]. On the other hand, drought and the severity of water deficit are key factors in water scarcity in arid and semi-arid regions of the world. These same regions are characterized by a rainfall pattern that concentrates the rainy season in a few months, leading to occasional urban floods as well. Therefore, currently, watersheds with urban areas that have overexploited aquifers, polluted surface waters, and lack of integrated water management, are facing...
a severe water crisis [3]. Consequently, managing water resources sustainably becomes a cornerstone. Therefore, the infiltrated water from urban agriculture areas (parks, golf courses, football stadiums, among others) that is not utilized by the crops could become a significant source of water capture for non-drinkable uses, replacing the volumes of drinking water currently used in those areas. In these cases, on-site water collection, storage, and reuse systems seem to be suitable technologies to implement in always-thirsty arid and semi-arid regions.

For tourist, social, sports, or environmental reasons, urban areas are provided with extensive grassy surfaces. These areas require large volumes of water to meet the needs of the plants, and depending on the climate, they may demand water volumes even higher than those allocated for human consumption. An example of the above is the issue related to water scarcity that occurs in the Mediterranean region, where one of the main water uses is for golf course watering. In Spain, by the end of the year 2020, the reported number of active golf courses was 500, ranking eleventh worldwide [4]. The irrigation of these courses represents an agricultural activity that uses significant amounts of water, equivalent to the water requirements of crops such as citrus, sunflower, and rice [5,6]. In fact, the average consumption of a standard 18-hole golf course in the Iberian Peninsula can range from 150,000 to 300,000 m³ year⁻¹ [7]. Based on these figures, the volume of water used annually could be equivalent to the annual supply for 3 million inhabitants, assuming an allocation of 130 l inhabitant⁻¹ day⁻¹ (average allocation for the Mediterranean region) [7]. The water demand of these golf courses is usually met, to a large extent, with groundwater, which clearly has a strategic nature, giving rise to two additional problems: (1) the diversion of significant volumes of water, with quality suitable for human consumption [8]; and (2) the use of agrochemicals partially utilized by the grass, which, due to their high solubility and inefficient management practices, promote the transport of pollutants through percolation to aquifers or through discharges into surface water bodies via runoff [9–11].

Given the present water scarcity and its worsening due to higher climate variability and climate change, it is necessary to improve water management, irrigation techniques, and fertilizer application [11,12], as well as to innovate and increase the use of green infrastructure (GI). This type of infrastructure is used to mitigate the impact of urban runoff from the source, and once captured, to promote its potential reutilization. Additionally, it is important to note that ten years ago, in 2013, the European Commission embraced the European Union Strategy on Adaptation to Climate Change (EUSACC). This strategy emphasized the necessity of implementing adaptation measures to mitigate climate change impacts at various levels, including the local, regional, and national [13,14]. The primary goal of EUSACC is to foster adaptation efforts centered around ecological infrastructures and ecosystems. To achieve this objective, it advocates for GI, recognizing that nature can provide long-lasting and economically sound solutions. Consequently, the GI serves as the guiding path toward Europe’s sustainable development, rooted in the principles of protecting and enhancing the natural environment, while integrating such infrastructure into territorial development plans [14,15]. Conversely, the Spanish Urban Agenda (SUA), aligned with international commitments under the 2030 Agenda, the UN’s New Urban Agenda, and the Urban Agenda for the European Union, places a strong emphasis on implementing comprehensive policies and strategies within cities. These initiatives aim to mitigate and adapt to climate change effects and enhance resilience to disasters [14,16]. In this context, the European Green Pact introduces innovative adaptation actions driven by green infrastructure (GI), with a particular focus on the sustainable urban drainage systems (SUDS). As a result, SUDS serve as elements that facilitate the management of urban stormwater and ensure compliance with European guidelines outlined in Directive 2000/60EC [14,17].

As outlined above, among GI options are SUDS, and here are referred to as SUDS-WR sustainable urban agriculture drainage systems with water reuse (SUDS-WR), which can be defined as GI technology used to manage rainwater, irrigation, surface waters, or some combination thereof, in a more sustainable way compared to conventional solutions.
Examples of these technologies include green roofs, rain gardens, infiltration trenches, among others [18]. These systems are designed to support the inherent ecological principles of the water cycle, fostering beneficial interactions between the socio-economic system and the urban water cycle. This approach enhances the adaptability and resilience of cities to changing environments and enables them to effectively cope with extreme weather events [19]. Additionally, compared to the traditional method of the immediate evacuation of the flows generated by a storm, GI technologies aim to regulate the volume of runoff, reduce the peak flow value generated by the storm, and increase the time to peak of the hydrograph in urban areas, as well as extend the recession curve, strengthening the resilience of the urban drainage system.

Rain gardens, also known as bioretention systems [19–21], have excellent characteristics to be implemented as SUADS-WR. In fact, these systems are green areas that absorb precipitation or irrigation water and are strategically located to capture surface runoff or even precipitation occurring on nearby impermeable areas such as roofs, streets, and roads. They become saturated after a storm, and then the water filters into the soil, being stored in a subsurface reservoir that captures the water exceeding the edaphic zone, for retention and/or reuse. The reduction in runoff volume using rain gardens improves water quality, reduces the load of pollutants into the surface and groundwater bodies, decreases the erosion rate, and helps mitigate water quality impacts from combined sewer overflows [22]. However, Gülbaz and Kazezyılmaz-Alhan [23] found that different soil characteristics can have significant effects on the hydrological regulation of flow through bioretention systems due to the varying infiltration capacities of soil combinations, such as vegetation, sand, and turf. This implies that each SUADS-WR must be designed based on the specific site characteristics and the crops involved.

On the other hand, it is worth remembering that infiltration is the process by which precipitation moves downward through the soil’s surface, replenishing soil moisture, recharging aquifers, and ultimately supporting streamflow during dry periods in a watershed [24]. The rate at which infiltration occurs is influenced by factors such as the type and extent of vegetal cover, the condition of the surface crust, temperature, rainfall intensity, the physical properties of the soil, and water quality. In fact, the rate at which water is transmitted through the surface layer is highly dependent on the condition of the surface. For instance, the presence of fine materials washing into the area can create a seal on the surface, leading to reduced infiltration rates, even in cases where the underlying soils have high permeability. Nonetheless, within the realm of bioretention systems, the soil depth typically remains shallow and is intentionally configured to house the root zone of the surface crop. It is essential to emphasize that engineering hydrology relies on two specific soil moisture levels, which will hold particular significance in this study for sizing the SUADS-WR system: field capacity and permanent wilting point. Field capacity represents the maximum quantity of moisture that the soil can retain against the force of gravity. It defines the upper threshold of moisture, beyond which any additional water tends to quickly pass through the soil. Conversely, the permanent wilting point signifies the soil moisture level at which plants initiate permanent wilting [24].

Soil moisture can be measured directly or indirectly. Direct measurement involves determining the weight loss of several oven-dried soil samples. Indirect measurement of soil moisture involves using tensiometers to measure the suction force with which water is held in moist soil. The device consists of a tube filled with water, featuring a porous cup at the bottom and a stopper on top. The drier the soil, the more water leaves the tube, resulting in a greater decrease in pressure. Tensiometer tests can be performed in situ, but their application is limited to a specific range of soil moisture levels.

Another indirect method for determining soil moisture is the water balance method. This method assumes that soil moisture can be represented as the difference between precipitation (input) and evapotranspiration (output). Hence, soil moisture content can be assessed directly using readily available precipitation and evapotranspiration data. To employ this method effectively, it is essential to establish a relationship between actual
evapotranspiration and soil moisture. When sufficient data are available, this method can yield valuable and accurate results [24].

Taking into account the described issue and the potential benefits of SUADS-WR, this study aims to propose a method for sizing the subsurface reservoir of the system based on a daily water balance, soil characteristics, and crop considerations. As an example, a design is presented with application in the context of green areas at the golf course “Club de campo del Mediterráneo,” located in the semi-arid region of southern Spain. With specific information from 2009 to 2011 of the experimental green constructed at the golf course [25,26], the hydrological performance of a SUADS-WR is simulated. For this purpose, hydro-informatics tools were developed that utilize hydrological models for water balance, soil–plant–water relationships, and the estimation of reference evapotranspiration, all of which have low requirements for climatic data. This process facilitates the estimation of the crop’s irrigation requirement, the value of the percolated water depth that exceeds the edaphic zone and is stored for reuse, as well as the retention of leached nitrogen and phosphorus to prevent them from contaminating surface or groundwater bodies.

The validation of this proposal is carried out by comparing the simulated results with observations from the experimental water balance, estimates of reference evapotranspiration using the Penman–Monteith method [27,28], and the quantification of leachates collected in the experimental green.

2. Materials and Methods
2.1. Study Area and Materials

The experimental green considered in this work was implemented by Bandenay [25] and had an area of 278 m². It was located at the golf course “Club de campo del Mediterráneo” in the southern region of Spain (Figure 1A,B). The green consisted of four experimental plots with a substrate composed of a sandy base of 26–40 cm above a layer of gravel of 10 cm. Drainage pipes were installed to transport the percolated water and leached compounds to a reservoir for control purposes. Each plot was lined up at the bottom and sides with a geomembrane to collect and independently channel all percolated water to the drainage outlet [26] (Figure 1C). The collected data from the experimental green (Figure 1C) includes the irrigation (R) and percolation (G) depths, as well as nitrogen and phosphorus leached concentrations. Additionally, the green was monitored with a weather station (Rain Bird Smart Weather®) that recorded precipitation (P), solar radiation, maximum and minimum temperatures, wind direction and speed, relative humidity, and allowed for the estimation of reference evapotranspiration (ET₀) using the Penman–Monteith equation [27,28]. Finally, the difference between input and output constitutes the change in water storage in the soil (∆RG).

The cultivated variety of grass in the experimental green was Agrostis stolonifera L-93, developed in the 1990s to be used as a sports turf, especially on golf course greens [29], which remain green throughout the year. Each plot was designed with a combination of different substrates (Table 1). Information on soil composition, organic matter content, water retention field capacity, and infiltration rate for each plot were also documented. It is important to highlight that plot P2 was constructed according to the specifications of the United States Golf Association (USGA) [30], which states that greens should contain sand and organic matter in a ratio of 80:20. Plot P4 only includes sand in its composition. The other construction designs were proposed to evaluate drainage and contaminant transport [26]. Some plots included peat (organic matter) and TerraCottem® (hydrogel), which is an amendment created from a mix of various acrylamide and acrylic acid copolymers, fertilizers, and volcanic rock, capable of forming water reserves in the soil. These compounds are often used to improve water and nutrient use efficiency.
Figure 1. Location and composition of the experimental green. (A) Location “Club de campo del Mediterráneo”; (B) polygon of “Club de campo del Mediterráneo”; and (C) composition of plots and conceptual model of the water balance of the experimental green.

Table 1. Characteristics of the experimental green plots at “Club de Campo del Mediterráneo” [25].

<table>
<thead>
<tr>
<th>Plot</th>
<th>Surface (m²)</th>
<th>Volume (m³)</th>
<th>Soil Composition</th>
<th>Organic Matter (%)</th>
<th>Water Retention Field Capacity (%)</th>
<th>Infiltration Rate (cm min⁻¹)</th>
<th>Bulk Density (g cm⁻³)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>37.5</td>
<td>10.5</td>
<td>80% Sand, 20% peat, 145 g m⁻² Hidrogel</td>
<td>4.045</td>
<td>35.56</td>
<td>0.69</td>
<td>1.467</td>
<td>40.14</td>
</tr>
<tr>
<td>P2</td>
<td>37.6</td>
<td>11.2</td>
<td>20% Organic matter, 80% Sand</td>
<td>7.397</td>
<td>45.83</td>
<td>1.26</td>
<td>1.394</td>
<td>51.65</td>
</tr>
<tr>
<td>P3</td>
<td>36.5</td>
<td>10.6</td>
<td>100% Sand, 145 g m⁻² Hidrogel</td>
<td>0.178</td>
<td>28.47</td>
<td>2.85</td>
<td>1.784</td>
<td>34.41</td>
</tr>
<tr>
<td>P4</td>
<td>35.4</td>
<td>9.3</td>
<td>100% Sand Hidrogel</td>
<td>0.139</td>
<td>26.75</td>
<td>3.38</td>
<td>1.684</td>
<td>34.88</td>
</tr>
</tbody>
</table>

In this study, only the data from plot P2 were used since it corresponds to the design specifications of golf courses [30] and is similar with other urban sports areas, such as football fields. It is worth noting that the USGA recommends a minimum infiltration rate of 0.25 cm min⁻¹ for new golf courses.

2.2. Methods

To determine the size of the subsurface reservoir for the SUADS-WR, it is necessary to perform a daily water balance simulation considering soil and crop characteristics. This process will facilitate estimating the crop’s irrigation requirement, as well as the volume of water percolated beyond the root zone and stored for reuse. Additionally, this
system will retain leached nitrogen and phosphorus to prevent them from contaminating surface or groundwater bodies. In fact, the system’s ability to retain these two chemical elements results from its function as a reservoir, with an impermeable liner covering 5 of its 6 faces. Hence, water enters through the soil and exits either through the upper side via evapotranspiration or through pumping the percolated water for reuse in irrigation purposes. It is worth noting that modeling the amounts of leached N and P is beyond the scope of this work. However, as an example, and using the experimental data collected by Bandenay [25], an estimation of the loads of these ions that could be prevented from percolating into the aquifer was made.

2.2.1. Experimental Water Balance in the Green

The green was planted and established in August 2008, and data collection continued until December 2011. For this study, data from 1 January 2009 to 31 December 2011 [25] were used as they correspond to the period during which information was recorded to estimate reference evapotranspiration using the Penman–Monteith method (\( ET_{0PM} \)). The equation for the daily water balance in the experimental green is expressed as equation (1), where the inputs of the balance are precipitation (\( P_i \)) and irrigation (\( R_i \)). The outputs are drainage or percolation (\( G_i \)) and water loss due to experimental evapotranspiration (\( ET_i \)) from the vegetation cover. The difference between input and output constitutes the daily change in water storage in the soil (\( \Delta RG_i \)).

\[
P_i + R_i = G_i + ET_i + \Delta RG_i
\]

(1)

The volume of irrigation input was quantified using data obtained from the measuring device connected to the irrigation system. The amount of water was determined based on the assumption that irrigation was applied uniformly. Precipitation and reference evapotranspiration (\( ET_{0PM} \)) were quantified using data from the weather station installed on site. The drainage volume was measured daily in the receivers specifically installed for this purpose. Experimental evapotranspiration (\( ET_i \)) was calculated from the experimental water balance, considering the volumes of water input and output in the plot, along with \( ET_{0PM} \) data. The outcome of this calculation led to the determination of an experimental crop coefficient denoted as \( Kc_e = 1.08 \). This determination was reported, for the case study, by Bandenay et al. [31]. Incorporating this latest finding and adopting a crop coefficient value of \( Kc = Kc_e = 1.08 \) enables the estimation of actual evapotranspiration (\( ETa \)). This estimation remains valid whether \( ET_{0PM} \) is considered or the Hargreaves–Samani method is utilized for calculating reference evapotranspiration (\( ET_{0HS} \)), as outlined by Hargreaves and Samani [32]. It is essential to recall that \( ETa \) for a given crop can be linked to \( ET_0 \) through the utilization of the crop coefficient as the product of \( ET_0 \) and \( Kc \), as detailed by Allen et al. [28]. Additionally, it is worth noting that \( Kc \) pertains to the specific attributes that differentiate the studied crop from a reference crop under standard, well-watered conditions. \( Kc \) varies based on factors such as the crop’s inherent nature, height, developmental stage, underlying substrate, and the prevailing climatic characteristics of the region. The value of \( Kc \) exhibits daily fluctuations and, for the purpose of simplification, is commonly expressed as an average over a period, either monthly, yearly, by stage of crop development, or season.

2.2.2. Estimated Water Balance for the Green

The daily water balance in the green was calculated based on the mathematical model proposed by Lagacé [33], which was, in turn, founded on the model suggested by Papineau [34]. This model estimates the irrigation depth based on the water content in the edaphic zone of the substrate. In other words, the amount of daily water present in the soil, \( RG_i \), was obtained using Equation (2).

\[
RG_i = RG_{i-1} + P \epsilon_i - ETa_i + R_i
\]

(2)
where \( R_{G_i} \) is the soil water storage value on day \( i \) (mm), \( R_{G_{i-1}} \) is the soil water storage value on the previous day to day \( i \) (mm), \( P_{e_i} \) is the effective precipitation on day \( i \) (mm), \( ET_{ai_i} \) is the actual evapotranspiration value on day \( i \) (mm), and \( R_i \) is the irrigation depth value on day \( i \) (mm).

It should be noted that the estimated water balance was carried out under two scenarios, one using the reference evapotranspiration value by the Penman–Monteith method \( (ET_{0PM}) \) and the other by the Hargreaves–Samani method \( (ET_{0HS}) \). Both estimations were compared with the observations collected from the experimental green, and the conceptual model for the estimated water balance considers a rain garden and irrigation system as a SUADS-WR.

Generally, for project or design purposes, crop evapotranspiration \( ET_c \) is used, while for evaluation or real-time irrigation forecasting, actual evapotranspiration \( ET_a \) is employed [35]. For this research, in the calculation of the variation in soil water storage \( \Delta R \), the reference evapotranspiration \( ET_0 \) was used because, in this case, it was equal to the crop evapotranspiration \( ET_c \) (Equation (3)) due to the value of \( K_c = k_c \) being equal to 1.08, which is very close to unity [31], and because \( ET_{0PM} \) was the value used in the experimental plot’s water balance. Thus, the estimation of crop evapotranspiration for day \( i \) \( (ET_{ci}) \) is given by Equation (3), where \( K_{ci} \) and \( ET_{0i} \) are, respectively, the crop coefficient for day \( i \) and the reference evapotranspiration for day \( i \).

\[
ET_{ci} = (K_{ci}) \cdot ET_{0i} \tag{3}
\]

It is also important to note that the Food and Agriculture Organization (UN-FAO) recommends the Penman–Monteith method for calculating reference evapotranspiration \( ET_0 \). However, since it requires the use of data that may not be available for every study area, it is advisable to use the method proposed by Hargreaves–Samani [32] to estimate \( ET_0 \). This method only requires data on maximum temperature, minimum temperature, and solar radiation. The general expression for \( ET_{0HS} \) is shown in Equation (4).

\[
ET_{0HSi} = 0.0135 \cdot (T_{medi} + 17.8) \cdot R_{si} \tag{4}
\]

where \( ET_{0HSi} \) is the reference evapotranspiration for day \( i \) estimated by the Hargreaves–Samani method, \( T_{medi} \) is the average of the maximum temperature of day \( i \) \( (T_{maxi}) \) and the minimum temperature of day \( i \) \( (T_{mini}) \), and the solar radiation of day \( i \) and \( R_{si} \) is estimated using equation 5 [36], which uses the extraterrestrial radiation \( R_{ai} \), obtained with Equations (6)–(9).

\[
R_{si} = (KT) \cdot (T_{maxi} - T_{mini})^{0.5} \cdot R_{ai} \tag{5}
\]

where \( R_{ai} \) is the incident solar radiation for day \( i \), \( R_{ai} \) is the extraterrestrial solar radiation for day \( i \), and \( T_{maxi} \) and \( T_{mini} \) are the maximum and minimum temperatures for day \( i \), respectively. The coefficient \( KT \) is an empirical coefficient that can be calculated from atmospheric pressure data. Hargreaves–Samani [36] recommend a value of \( KT = 0.162 \) for inland regions and \( KT = 0.19 \) for coastal regions. However, a commonly used value is \( KT = 0.17 \) [37]. The extraterrestrial solar radiation \( (R_{ai}) \) is estimated for each day of the year and any latitude using Equation (6) [28].

\[
R_{ai} = \frac{24}{\pi} \cdot G_{sc} \cdot d_{si} \left[ \omega_{si} \sin(\phi) \sin(\delta_i) + \cos(\phi) \cos(\delta_i) \sin(\omega_{si}) \right] \tag{6}
\]

where \( R_{ai} \) is the extraterrestrial radiation for day \( i \), expressed in units of MJ m\(^{-2}\) day\(^{-1}\), but converted to mm day\(^{-1}\) by multiplying by the factor 0.408, \( \phi \) is the latitude of the site in radians, \( G_{sc} \) is the solar constant with a value of 0.082 MJ m\(^{-2}\) min\(^{-1}\), \( d_{si} \) is the inverse relative distance of the Earth to the Sun for day \( i \) (Equation (7)), \( \delta_i \) is the solar declination in radians for day \( i \) (Equation (8)), and \( \omega_{si} \) is the sunset hour angle in radians.
for day $i$ (Equation (9)). These equations also require the day of the year $J_i$ [28], where $J_{i=1}$ corresponds to 1 January.

$$d_{r_i} = 1 + 0.033 \cos \left( \frac{2 \pi}{365} J_i \right)$$

$$\delta_i = 0.409 \sin \left( \frac{2 \pi}{365} J_i - 1.39 \right)$$

$$\omega_{s, i} = \arccos \left[ -\tan(\varphi) \tan(\delta_i) \right]$$

On the other hand, effective precipitation $P_{e}$ is defined as the proportion of precipitation that can potentially be available in the edaphic zone and is the moisture that the plant utilizes to meet its water requirements. Estimating the daily effective precipitation $P_{ei}$ is very complex as it depends on several factors. However, it can be estimated using expressions such as Equations (10) and (11) proposed for real-time irrigation forecasting, which consider values of crop evapotranspiration for day $i$ ($E_{TC_i}$) and the precipitation for day $i$ ($P_i$), both in mm. It also requires the calculation of the function $f(HTU)$ that depends on the total usable moisture on day $i$ ($HTU$) [35].

$$P_{ei} = f(HTU) \left[ 1.25 P_i^{0.824} - 2.93 \right] 10^{0.000935 E_{TC_i}}$$

$$f(HTU) = 0.53 + 0.0116 HTU - 8.94 \times 10^{-5} (HTU)^2 + 2.32 \times 10^{-7} (HTU)^3$$

The water content in the soil can be considered to be stored in two sections: the root zone ($RG$) and a storage zone ($SG$). By knowing the amount of water in the root zone, it is possible to propose the irrigation depth ($R$) necessary to meet the turf’s requirements. Similarly, by knowing the amount of water in the storage zone, it is possible to estimate the value of the percolated depth ($G$), which can be reused. The essential information regarding the soil’s hydraulic properties and knowing the stored water content available for crop consumption are the field capacity ($\theta_{CC}$) and the permanent wilting point ($\theta_{PMP}$). Here, it is worth remembering that the field capacity ($\theta_{CC}$) of a soil represents the maximum amount of water that can be retained in the soil against gravity after irrigation or rainfall thoroughly wetted the soil [38]. The concept of permanent wilting point derives from the experiences of Briggs and Shantz [39]. When the soil reaches field capacity, it progressively loses water through evapotranspiration as the plants absorb the water. There comes a point where the plants can no longer absorb more water because no water is available, leading them to irreversibly wilt. At this moment, the soil reached the permanent wilting point. This state marks the lower limit of water utilization by the plants [40]. For estimating the field capacity, it is possible to use the Peele model [41] shown by Equation (12), and to estimate the permanent wilting point, Equation (13) is used [39].

$$\theta_{CC} = 0.48 Ac + 1.62 Li + 0.023 Ar + 2.62$$

$$\theta_{PMP} = 0.302 Ac + 0.102 Li + 0.0147 Ar$$

where $\theta_{CC}$ is the soil moisture at field capacity expressed as gravimetric moisture (%), $\theta_{PMP}$ is the soil moisture at the permanent wilting point, expressed as gravimetric moisture (%), $Ac$ is the clay content (%), $Li$ is the silt content (%), and $Ar$ is the sand content (%). However, Angeles et al. [42] propose the Saxton model [43] to estimate the soil hydraulic properties. These authors argue that this model is suitable for calculating field capacity and permanent wilting point and is expressed only based on the percentage of sand and clay in the soil under study, using Equations (14)–(17), where $C_A$ and $C_B$ are dummy
variables used as helpers for the estimation of $\theta_{CC}$ and $\theta_{PMP}$. It is worth noting that to determine $\theta_{CC}$ and $\theta_{PMP}$ based on the granulometric information, the hydro-informatics tool developed incorporated the Saxton model, which provides smaller irrigation depths in a shorter period, thus being closer to reality.

$$\theta_{CC} = \left( \frac{1}{3} C_A \right)^{\frac{1}{\gamma}}$$  \hspace{1cm} (14)

$$\theta_{PMP} = \left( \frac{-15}{C_A} \right)^{\frac{1}{\gamma}}$$  \hspace{1cm} (15)

$$C_A = e^{-[(4.285 \times 10^{-5}) A r^2 A c + (4.88 \times 10^{-4}) A r^2 + 0.0715 A c + 4.396]}$$  \hspace{1cm} (16)

$$C_B = -\left[ (3.484 \times 10^{-5}) A r^2 A c + 0.00222 A c^2 + 3.14 \right]$$  \hspace{1cm} (17)

In theory, although the water available to crops in the soil is the range between the moisture content at field capacity and the moisture content at the permanent wilting point ($\theta_{CC} - \theta_{PMP}$), not all species can extract that amount of water. For this reason, a physiological characteristic factor was introduced, indicating the fraction of usable moisture from which the crop begins to show adverse physiological symptoms (chlorosis, reduced growth, decreased yield, wilting, etc.). This concept is known as the fraction of readily available soil water ($f_o$). Allen et al. [28] propose $f_o = 0.5$ for turf. This concept establishes a critical point ($\theta_{PC}$) for soil moisture conditions and can be estimated using Equation (18).

$$\theta_{PC} = \theta_{CC} - (\theta_{CC} - \theta_{PMP}) f_o$$  \hspace{1cm} (18)

Knowing the depth colonized by the roots ($Rd$), it can be inferred that from the total available moisture ($HTU$) expressed in water depth using Equation (19), each crop has the physiological capacity to utilize only a fraction, which is known as readily usable moisture ($HFU$) and is expressed in water depth using Equation (20).

$$HTU = Rd (\theta_{CC} - \theta_{PMP})$$  \hspace{1cm} (19)

$$HFU = (HTU) f_o = Rd (\theta_{CC} - \theta_{PMP}) f_o$$  \hspace{1cm} (20)

Once the water depth at field capacity, permanent wilting point, and critical point in the edaphic zone are obtained, along with the proposed initial soil moisture conditions, the water balance begins considering the known variables. That is, the inputs by $Pe_i$ and the outputs by $ET_i$, from which the daily change in water storage in the soil $\Delta G_i$ is calculated using Equation (21).

$$\Delta G_i = Pe_i - ET_i$$  \hspace{1cm} (21)

If $\Delta G_i$ is less than zero, the water depth is extracted from the root zone $RG_i$, which initially starts at field capacity; thus, it dries first, and the water level in the reservoir or storage $SG_i$ remains the same as the previous day. If $\Delta G_i$ is greater than zero, water is added to the soil, and the additional depth is sent to the reservoir zone $SG_i$. The moisture in the root zone $RG_i$ is maintained because a well-drained soil is considered [33].

2.2.3. The Irrigation Depths and Storage in the Subsurface Reservoir

To determine the required irrigation depth $R_i$, it is necessary to consider the amount of water in the root zone $RG_i$. This value decreases from the initial field capacity $\theta_{CC}$ as the soil loses water due to evapotranspiration until reaching the critical point $\theta_{PC}$. At the critical point, it is necessary to supply the required amount of water through irrigation $R_i$.
to return to the field capacity. The equations to calculate the water content in the root zone and determine the daily irrigation depth are shown in Equations (22)–(25).

\[
RG_i = \begin{cases} 
RG_{i-1} + \Delta G_i, & \Delta G_i = Pe_i - ET_i \leq 0 \\
RG_{i-1}, & \Delta G_i = Pe_i - ET_i > 0
\end{cases}
\]

\[
RG_i = \begin{cases} 
\theta_{CC}, & RG_i < \theta_{PC} \\
RG_i, & RG_i > \theta_{PC}
\end{cases}
\]

\[
R_i = \begin{cases} 
RG_i - RG_{i-1} - \Delta G_i, & \Delta G_i = Pe_i - ET_i \leq 0 \\
RG_i - RG_{i-1}, & \Delta G_i = Pe_i - ET_i > 0
\end{cases}
\]

\[
R_i = \begin{cases} 
R_i, & RG_i = \theta_{cc} \\
0, & RG_i \neq \theta_{cc}
\end{cases}
\]

To estimate the depth sent to the subsurface reservoir \(SG_i\), in addition to considering the value of the reserve \(\Delta G_i\) when it is positive, the difference between precipitation and effective precipitation \((E_{si} = P_i - Pe_i)\) must also be included. Therefore, in the drainage depth and the estimated water balance, all the outputs generated by precipitation are considered, ensuring that the comparison between the experimental green’s balance and the estimated balance is consistent.

\[
SG_i = \begin{cases} 
E_{si}, & E_{si} \\ E_{si} + \Delta G_i, & \Delta G_i = Pe_i - ET_i \leq 0 \\
\Delta G_i, & \Delta G_i = Pe_i - ET_i > 0
\end{cases}
\]

2.2.4. Irrigation Depth Considering Salt Leaching

Evapotranspiration removes only water that is transferred to the atmosphere, leaving salts in the soil and concentrating the remaining solution. Therefore, it is necessary to add a fraction of water to the irrigation depth for leaching these salts and moving them away from the edaphic zone [42]. The concentration of salts varies as the soil water content changes, so the soil salinity is measured and expressed based on the electrical conductivity of the soil saturation extract \((CE_e)\). The \(CE_e\) is defined as the electrical conductivity of the soil water solution after adding enough distilled water to bring the soil water content to saturation. Typically, it is expressed in deciSiemens per meter \((dS m^{-1})\) [28]. The estimation of the additional irrigation needed for salt leaching is calculated with Equation (27) [42].

\[
RL_i = R_i \left( \frac{1}{1 + \frac{CE_e}{CE_{el}}} \right)
\]

where \(RL_i\) is the irrigation depth for day \(i\) that considers soil leaching in mm, \(R_i\) is the irrigation depth for day \(i\), \(CE_e\) is the electrical conductivity of the irrigation water in dS m\(^{-1}\), and \(CE_{el}\) is the electrical conductivity of the soil saturation extract that does not produce a reduction in crop yield in dS m\(^{-1}\) [28], a value that depends on the crop’s salt tolerance. For turfgrass, \(CE_{el} = 6.9\) dS m\(^{-1}\). The leaching depth is particularly important in arid regions where rainwater does not wash salts away from the root zone. It is also considered that in cultivated areas where there are seasons with abundant rainfall, it may not be necessary to leach salts from the irrigation water, as the frequent rain events will naturally dilute the salts.

2.2.5. Optimal Height of the Harvested Water Storage Tank

To propose the optimal height of the harvested water storage tank, part of the method proposed by Fonseca et al. [44] was used, where they consider available rainfall data and the estimated storage efficiency based on a daily mass balance model. In this mass balance,
the efficiency of supply in period $j$ is represented by a relationship of the accumulated daily deficit and demand, as shown in Equation (28).

$$\text{Ef}_j = 1 - \frac{\sum \text{Def}_i}{\sum \text{R}_i}$$  \hspace{1cm} (28)

where $\text{Ef}_j$ is the efficiency of supply, which in this case is the stored percolation, $\sum \text{Def}_i$ is the sum of deficits in the considered period, and $\sum \text{R}_i$ is the sum of the irrigation depth, which can be considered with or without leaching, depending on the case. On the other hand, to calculate the deficit and the amount of water in the storage tank, Equations (29) and (30) were used, respectively.

$$\text{Def}_i = \begin{cases} 0, & \text{SG}_i + \text{SG}_{i-1} \geq \text{R}_i \\ \text{R}_i - \text{SG}_i - \text{SG}_{i-1}, & \text{SG}_i + \text{SG}_{i-1} < \text{R}_i \end{cases}$$  \hspace{1cm} (29)

$$\text{SG}_i = \begin{cases} 0, & \text{Gp}_i + \text{SG}_{i-1} \leq \text{R}_i \\ \text{SG}_i + \text{SG}_{i-1} - \text{R}_i, & \text{SG}_i + \text{SG}_{i-1} > \text{R}_i \\ \text{S}, & \text{SG}_i + \text{SG}_{i-1} - \text{R}_i \geq \text{S} \end{cases}$$  \hspace{1cm} (30)

where $\text{SG}_i$ is the value of percolation (the supply), $\text{R}_i$ is the daily irrigation depth (the demand), both data in mm, obtained with the water balance module, $\text{SG}_{i-1}$ is the daily amount of water in the rain garden storage tank in mm, and $\text{S}$ is the storage height proposed by the user in mm.

With these equations, it is possible to estimate the efficiency for each proposed storage height and calculate a second efficiency for a tank 100 mm higher. By obtaining the two efficiencies for each storage height, the difference between them is calculated. When the difference between the efficiencies of the two tanks is minimal or equal to zero, the proposed storage height corresponds to the smaller size, representing the optimal or acceptable height.

### 2.2.6. Statistical Performance Criteria between ET$_{0\text{PMi}}$ and ET$_{0\text{HSi}}$

To evaluate the performance of the ET$_{0\text{PMi}}$ and ET$_{0\text{HSi}}$ methods in this study, it is possible to calculate the statistical metrics such as the Pearson’s correlation coefficient ($r$), the coefficient of determination ($r^2$), the Nash–Sutcliffe efficiency (NSE), and PBIAS (percent bias); $r$ and $r^2$ are widely used in hydrological modeling studies and serve as benchmarks for performance evaluation [45]. The Nash–Sutcliffe efficiency (NSE) is used to determine how well the model simulates trends for the output response of interest; it is used to evaluate the model performance for several case studies and temporal scales. Additionally, NSE can incorporate measurement uncertainty [46,47]. The percent bias (PBIAS) criterion measures the average trend of simulated values that are above or below the observed values. The optimal value of PBIAS is zero, where low-magnitude values indicate an accurate simulation of the model. Negative values indicate an overestimation bias, while positive values indicate an underestimation bias of the model.

Equations (31)–(33) allow the calculation of the statistics $r$, $r^2$, and NSE, respectively, considering the data of ET$_{0\text{PMi}}$ as the observed values and the data estimated with the method ET$_{0\text{HSi}}$ as the estimated values. ET$_{0\text{PMi}}$ and ET$_{0\text{HSi}}$ are the respective mathematical expectations of the reference evapotranspiration values by the Penman–Monteith or Hargreaves–Samani method for the analyzed period.

$$r = \frac{\sum_{i=1}^{n} (\text{ET}_{0\text{PMi}} - \overline{\text{ET}_{0\text{PMi}}}) (\text{ET}_{0\text{HSi}} - \overline{\text{ET}_{0\text{HSi}}})}{\sqrt{\sum_{i=1}^{n} (\text{ET}_{0\text{PMi}} - \overline{\text{ET}_{0\text{PMi}}})^2} \sqrt{\sum_{i=1}^{n} (\text{ET}_{0\text{HSi}} - \overline{\text{ET}_{0\text{HSi}}})^2}}$$  \hspace{1cm} (31)

$$r^2 = (r)^2$$  \hspace{1cm} (32)
The use of simulation to model hydrological systems became essential, and although there are different programming languages and software development programs, one of the most popular programs, widely used in recent decades for building hydrological models, is MATLAB (MATrix LABoratory) [48].

To solve the proposed methods in this work for the sizing of the SUADS-WR and the estimation of the irrigation depth of the system, two hydro-informatics tools were developed in MATLAB. The first tool performs the daily water balance, providing the estimation of evapotranspiration using the Hargreaves–Samani method, as well as the estimation of the required irrigation depth and the percolation that can be stored. The second tool, using the results obtained from the percolation (supply) and irrigation depth (demand) for the operational years of the system, facilitates the estimation of the optimal height of the subsurface reservoir in the SUADS-WR. These hydro-informatics tools developed in this work are available to readers upon request addressed to the authors of this study.

### 3. Results

#### 3.1. Estimated Daily Water Balances Using the Hydro-Informatics Tool

In the first simulation scenario of the water balance, the irrigation depths \( R_i \) and drainage amounts \( G_i \) were estimated using the same daily evapotranspiration \( ET_{0PMi} \) and precipitation \( P_i \) data as the balance obtained in the experimental study. To ensure that the estimated water balance aligns with the experimental green, an equivalent substrate size distribution particle was used to obtain a field capacity value that closely matches the experimental value obtained in the green.

It is worth noting that in the laboratory, a homogeneous soil mixture can be obtained. However, the composition of the plots is not necessarily homogeneous. Therefore, for plot P2, which contains a proportion of organic matter in the root zone, a composition of 35% sand and 65% clay was proposed, obtaining a field capacity value of 45.76%, very close to the 45.86% recorded for the experimental plot P2. With the given data, the agronomic parameters of field capacity \( \theta_{CC} = 137 \) mm, critical point \( \theta_{PC} = 122 \) mm, permanent wilting point \( \theta_{PMP} = 107 \) mm, total available moisture \( HTU = 30 \) mm, readily available moisture \( HFU = 15 \) mm, and \( f(HTU) = 0.8055 \) were obtained. The value of \( f(HTU) \) (Equation (11)) was used to estimate the daily effective precipitation (Equation (10)) and depends on the total available moisture \( HTU \) (Equation (19)).

Using the estimation of field capacity and critical point (Equations (14)–(18)), it was possible to propose the initial moisture conditions and moisture limits for the root zone \( RG \), which must always have a water depth between 122 and 137 mm for proper turf development. The initial moisture content of the root zone should be the field capacity moisture content, which was 137 mm. Using Equations (10) and (11), the daily effective precipitation \( Pe_i \) was estimated to obtain the soil water reserve \( \Delta G_i \) with Equation (21). Both values required the crop evapotranspiration \( ET_c \), for their estimation.

With the soil water reserve \( \Delta G_i \), Equations (22) and (23) were used to obtain the amount of water on day \( i \) in the root zone \( RG_i \). Subsequently, Equations (24) and (25) were used to calculate the daily irrigation depth \( R_i \), and Equations (26) and (27) were used to determine the amount of water accumulated in the subsurface reservoir \( SG \). With the daily data obtained from the water amount in the reservoir, it was possible to calculate the depth of water that percolated beyond the root zone or even the annual drainage rate, denoted as \( G \), by subtracting the accumulated amount in the reservoir on the last day of year \( j \),

\[
NSE = 1 - \frac{\sum_{i=1}^{n} (ET_{0PMi} - ET_{0HSi})^2}{\sum_{i=1}^{n} (ET_{0PMi} - ET_{0PMi})^2}
\]  
\[
PBIAS = \frac{\sum_{i=1}^{n} (ET_{0PMi} - ET_{0HSi})}{\sum_{i=1}^{n} ET_{0PMi}} \times 100
\]
SG_{365j} from the amount that was there on the first day of the year, SG_{1j}. Additionally, using Equation (24), it was possible to obtain the value of the irrigation depth that also takes into account salt leaching.

Using the data obtained from the simulated water balance for plot P2, it was possible to make a comparison with the water balance derived from the experimental study. The simulated annual water balances of plot P2 considered the daily evapotranspiration data using the ET_{0PM} method. These balances considered the leaching irrigation RL and that its application did not show drainage discharges, meaning the drainage depth was only produced by precipitation. It is worth noting that the simulated balance provides a more stable irrigation depth for each year (Table 2).

![Table 2. Comparison of annual balances for plot P2 (ET_{0PM} y ET_{0HS}).](image)

In the next simulation scenario of the water balance, the irrigation depth R and drainage depth G were obtained using daily evaportranspiration data calculated with the ET_{0HS} method for plot P2. The data used to derive the agronomic parameters were the same as those used in the previous balance. The ET_{0HS} method only required daily data of minimum and maximum temperatures, as well as location data such as latitude and the coefficient KT, for coastal or inland areas. In this case, a coefficient KT = 0.17 was used. Once the ET_{0HS} and water balance were estimated with the corresponding tool, a comparison was made against the water balance obtained from the experimental study. In the same way, a comparison was made between the estimates obtained by both methods, where it was possible to observe that the drainage depth exhibits minimal variation, while the irrigation depth remains consistently similar, implying an annual irrigation water requirement of one meter per square meter of lawn. Furthermore, when comparing the three estimates, it can be observed that the irrigation depth remains lower in the estimated balances than the one applied empirically in plot P2 of the experimental green (Table 2).

Using the daily data from the ET_{0PM} and ET_{0HS} methods, it was possible to create a scatter plot where the ET_{0PM} values are represented on the x-axis and the ET_{0HS} values on the y-axis to show the level of accuracy achieved in estimating evapotranspiration (ET). In Figure 2, the scatter plot is observed, indicating an overestimation of ET with the ET_{0HS} method, as most points lie above the 45° line.

On the other hand, according to equations 31, 32, and 33, the coefficient of determination had a value of $r^2 = 0.7052$, revealing a positive correlation of $r = 0.8398$. The NSE coefficient was 0.6, which, according to Moriasi et al. [45], is classified as a satisfactory value. The result of PBIAS = −11.66% is also considered satisfactory and confirms the slight tendency of the ET_{0HS} method to overestimate the ET value when compared to the actual value of ET_{0PM}.
3.2. Irrigation Depths Comparison

For the development of the methods that facilitate obtaining the irrigation depth of the lawn using Equations (22)–(25), it was necessary to know the daily amount of water in the soil, depending on its agronomic parameters. Indeed, the daily changes in water in the root zone provided the necessary information to decide when and how much volume to irrigate. Additionally, the water depth that was not absorbed by the plant helps estimate how much water percolates and can be collected.

In Figure 3A, the results of the daily water content in the root zone are shown for the estimated balance with the ET0PM method of plot P2. In Figure 3B, the applied irrigation depth is displayed in red, and the estimated irrigation depth considering leaching is shown in blue. In Figure 3C, the accumulated irrigation depth applied in plot P2 is shown in red, compared to the accumulated estimated irrigation depth in blue, confirming that the irrigation depth applied during the experimental phase was higher than required.

The area between the accumulated applied irrigation and the accumulated estimated irrigation (Figure 3C) represents the amount of water that could be saved in irrigation by using the methods and GI here proposed. It is worth noting that the irrigation depth to be applied to a substrate such as that of plot P2, using both the ET0PM and ET0HS methods, ranges between 15 and 20 mm per irrigation with extended irrigation intervals, considering the soil’s storage capacity.

The ET0HS method used in this study to estimate reference evapotranspiration produces reliable results for obtaining the irrigation depth (Table 3). Under this method, a maximum difference of 10% per year was found compared to the Penman–Monteith method, making it recommended for use in sites where sufficient information for evapotranspiration estimation using the latter method is not available. Additionally, it is possible to compare the ET0PM method considering leaching against the irrigation obtained with the ET0HS method without considering leaching, as this latter method could be used to obtain irrigation including salt leaching without additional calculations (Table 3).
Figure 3. Irrigation depths in plot P2 with $ET_{0PM}$. (A) Water content in the root zone ($RG$). (B) Estimated irrigation depth vs. applied irrigation depth. (C) Accumulated estimated irrigation depth (blue line) vs. applied irrigation depth (red line).

Table 3. Difference between applied irrigation in plot P2 against irrigation estimated with leaching, and between applied irrigation, irrigation with leaching and $ET_{0PM}$, and irrigation without leaching and $ET_{0HS}$.

<table>
<thead>
<tr>
<th>Year</th>
<th>Applied Irrigation in Plot P2 (mm Year$^{-1}$)</th>
<th>Estimated Irrigation. $ET_{0PM}$ (mm Year$^{-1}$)</th>
<th>Estimated Irrigation. $ET_{0HS}$ (mm Year$^{-1}$)</th>
<th>Irrigation$_{PM}$ and Experimental Irrigation Difference (mm Year$^{-1}$)</th>
<th>Irrigation$_{HS}$ and Experimental Irrigation Difference (mm Year$^{-1}$)</th>
<th>Difference between Estimated Irrigations (mm Year$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>1004</td>
<td>943</td>
<td>1053</td>
<td>61</td>
<td>−49</td>
<td>110</td>
</tr>
<tr>
<td>2010</td>
<td>1578</td>
<td>972</td>
<td>1077</td>
<td>579</td>
<td>501</td>
<td>105</td>
</tr>
<tr>
<td>2011</td>
<td>1180</td>
<td>999</td>
<td>1098</td>
<td>181</td>
<td>82</td>
<td>99</td>
</tr>
</tbody>
</table>

Irrigation depth: applied in plot P2; estimated with leaching using the $PM$ method and estimated with leaching using the $HS$ method.

3.3. Design of the Rainwater Harvesting Bioretention System

The materials that make up the proposed rainwater harvesting bioretention system can be seen in Figure 4. With this system, the importance of implementing SUADS-WR...
is emphasized, which not only utilizes percolated rainwater and the percolation from irrigation that is not absorbed by the lawn, but also recycles leached fertilizers, protecting water quality in aquifers and reducing groundwater extraction.

![Proposed rainwater-harvesting bioretention system SWADS-WR type.](image)

**Figure 4.** Proposed rainwater-harvesting bioretention system SWADS-WR type.

With the second hydro-informatics tool developed, it was possible to propose an optimal height for the rainwater percolation storage tank in the SUADS-WR. Using the daily data from the analyzed 3-year period and applying Equations (29)–(31), a theoretical storage height of 350 mm was obtained for the study case. However, by considering a storage height of 300 mm and another hypothetical height of 400 mm, the difference in efficiencies between the 300 mm and 400 mm storage was only 0.6%. As a result, a storage height of 300 mm was selected. In Figure 5A, the performance of the water quantity in the storage tank, considering inflows from percolation and outflows from irrigation, is shown. In Figure 5B, the irrigation deficit, which is the amount of water that cannot be supplied with the harvested water, is observed. Lastly, in Figure 5C, the excess drainage once the storage tank is filled is shown.

Based on the information derived from the daily deficit of irrigation depth, as obtained through the utilization of the second hydro-informatics tool developed, it became possible to estimate the annual irrigation depth required, considering both harvesting and the reuse of percolation with the SUADS-WR system. Moreover, the percentage of percolation available for irrigation each year could also be determined. Consequently, the findings indicate the feasibility of providing over one-third of the annual irrigation depth for the lawn using stored percolated precipitation, particularly in regions characterized by limited rainfall, such as the case in the Spanish Mediterranean region (Table 4).

On the other hand, the concentrations of nitrates (NO$_3^-$) in the leached water are influenced by the amount of fertilizer applied and the water input. Consequently, concentrations ranged from a maximum of 141 to a minimum of 5.2 mg L$^{-1}$, with an average of 27.5 mg L$^{-1}$ having occurred [26]. This average value is lower than the drinking water limit established in Spain, which is 50 mg L$^{-1}$. Conversely, average phosphate concentrations in the leachate did not exceed 8 mg L$^{-1}$ (27.7–0.7 mg PO$_4^{3-}$ L$^{-1}$). In this case, leaching is primarily regulated by the low solubility of phosphorus compounds [20]. Additionally, it is worth noting that there is no established limit value for phosphorus [49].
findings indicate the feasibility of providing over one-third of the annual irrigation depth for the lawn using stored percolated precipitation, particularly in regions characterized by limited rainfall, such as the case in the Spanish Mediterranean region (Table 4).

Figure 5. Performance of the optimal storage. (A) Water content in the storage. (B) Irrigation deficit. (C) Drainage from the storage.

Table 4. Difference between estimated irrigations and harvested depth.

<table>
<thead>
<tr>
<th>Year</th>
<th>Estimated Irrigation Depth. (mm Year⁻¹)</th>
<th>Harvested Water. (mm Year⁻¹)</th>
<th>Irrigation Water Deficit (mm Year⁻¹)</th>
<th>Percentage of Water Reused. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Harvested water using ET₀PM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>943</td>
<td>547</td>
<td>396</td>
<td>58</td>
</tr>
<tr>
<td>2010</td>
<td>972</td>
<td>366</td>
<td>606</td>
<td>38</td>
</tr>
<tr>
<td>2011</td>
<td>999</td>
<td>437</td>
<td>562</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>Harvested water using ET₀HS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>1053</td>
<td>540</td>
<td>513</td>
<td>51</td>
</tr>
<tr>
<td>2011</td>
<td>1077</td>
<td>354</td>
<td>723</td>
<td>33</td>
</tr>
<tr>
<td>2009</td>
<td>1098</td>
<td>428</td>
<td>670</td>
<td>39</td>
</tr>
</tbody>
</table>

Regarding the protection against groundwater pollution using a SUADS-WR, if we consider an irrigated area of one hectare, approximately 0.5 to 1 ton of nitrogen and 0.15 to 0.3 tons of phosphorus are leached per year [25]. The total area of the golf course greens in the Mediterranean is 122,454 m², which is equivalent to 12.5 hectares. Therefore, for this specific golf course, it was estimated that 6 to 12 tons of nitrogen and between 1.8 and 3.7 tons of phosphorus would be leached annually (Table 5).
Table 5. Leached fertilizers from plot P2 [25].

<table>
<thead>
<tr>
<th>Irrigation Period (mm/dd/yyyy)</th>
<th>Output N (g)</th>
<th>Output P (g)</th>
<th>Output N (kg ha$^{-1}$)</th>
<th>Output P (kg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>05/28/2009 - 07/21/2009</td>
<td>11.83</td>
<td>1.96</td>
<td>118.3</td>
<td>19.6</td>
</tr>
<tr>
<td>07/22/2009 - 10/14/2009</td>
<td>28.33</td>
<td>12.20</td>
<td>283.3</td>
<td>122.0</td>
</tr>
<tr>
<td>10/15/2009 - 09/11/2009</td>
<td>1.05</td>
<td>1.43</td>
<td>10.5</td>
<td>14.3</td>
</tr>
<tr>
<td>10/11/2009 - 03/03/2010</td>
<td>57.65</td>
<td>18.79</td>
<td>576.5</td>
<td>187.9</td>
</tr>
<tr>
<td>04/03/2010 - 05/20/2010</td>
<td>31.56</td>
<td>5.91</td>
<td>315.6</td>
<td>59.1</td>
</tr>
<tr>
<td>05/21/2010 - 07/07/2010</td>
<td>19.63</td>
<td>4.81</td>
<td>196.3</td>
<td>48.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>160.05</strong></td>
<td><strong>45.1</strong></td>
<td><strong>1600.5</strong></td>
<td><strong>451</strong></td>
</tr>
</tbody>
</table>

4. Discussion

In light of the prevailing water scarcity across arid and semi-arid regions and the urgent need to safeguard water resources to meet future demands, it becomes strategic to establish water services that are socially, economically, and environmentally sustainable. Within this framework, water reuse plays an important role in integrated water management, particularly in urban environments, and forms a key component of the toolkit necessary for achieving sustainability. However, successfully implementing sustainable urban water management that adapts to the impacts of climate change and climatic variations is difficult to define and measure, and there is no simple or unique solution for this. Concerning water supply side and demand-side measures, the latter is perceived to be more important and reliable than the former. Hence, there are at least three main reasons supporting the promotion of water reuse as a water demand measure. Firstly, it helps mitigate the environmental impact caused by releasing low-quality water into surface water bodies or allowing it to infiltrate into the groundwater. Secondly, it enhances the availability of water to meet the demand for high-quality water. Thirdly, it leads to a reduction in potable water demand for urban agriculture. Nevertheless, economic and financial considerations play a critical role as they directly impact the feasibility of such initiatives and could possibly restrict the full potential of water reuse for specific purposes (i.e., irrigation of parks, golf courses, football field, among other urban green surfaces). In fact, it is important to acknowledge that stakeholders may not be prepared to accept recycled water for drinking purposes. Instead, its preferred use is for non-drinkable applications. Furthermore, the careful utilization of treated wastewater, as well as some stormwater, in agriculture is needed to prevent potential health risks to consumers. Sewage water contains microbial pathogens that can present biological hazards to both humans and vegetation. Consequently, it is necessary to prioritize and closely monitor the reuse of treated wastewater in agricultural practices and irrigation. Although this water contains essential nutrients that could reduce the reliance on additional fertilizers and potentially improve crop productivity, ensuring safety remains paramount. In this regard, implementing a SUADS-WR can help overcome several of the limitations, at least for urban agriculture. In fact, rainwater harvesting and site retention play a crucial role in local water protection, ensuring that the retained water quality remains suitable for reuse within the same urban green field. Even though the harvested water is enriched with fertilizers and other compounds, it retains good quality, making it safe for irrigating grass and suitable for both grass crops and human contact activities.

On the other hand, the results of this work not only agree with the findings of Gdanskie Wody [50], who states that the initial precipitation or irrigation sheet up to 20–30 mm must be retained by urban vegetation and soil moisture to reach field capacity, but it is also possible to refine the irrigation range from 15 to 22 mm. Rainfall or irrigation greater than 22 mm, according to the proposed design, will be directed to the SUADS-WR subsurface reservoirs. Excess rainwater could reach the municipal storm drainage system or, failing that, the surface water receiving bodies. Moreover, according to Sánchez-Almodóvar et al. [14], SUDS are useful in events not exceeding 100 mm h$^{-1}$. They also stress that in semi-arid and Mediterranean climate areas, their effectiveness is very high for rainfall events between 35 and 50 mm h$^{-1}$ and durations up to two and a half hours.
It is also worth mentioning that in the design of the SUADS-WR subsurface reservoir, an effective retention volume of 80% of the total volume of each module was considered. In fact, 20% of the volume of each module represents the structural requirements of the tank-forming module. However, it is also important to highlight that this structural analysis is beyond the scope of this work.

Another advantage of SUADS-WR is the mitigation of the heat island effect, as mentioned by Kasprzyk et al. [51]. They found, through the evaluation of thermal camera shots, a thermal difference of up to 20 °C compared to other open surfaces (such as parking pavement) in sunny weather with an air temperature of 21 °C. Therefore, in the case study of arid or semi-arid lands, these temperatures, or even higher, are very frequent. On the other hand, SUADS-WR has the potential to address several urban circularity challenges (UCCs) simultaneously. In fact, among the seven urban circularity challenges (UCCs) identified by Atanasova et al. [52] and Kasprzyk et al. [51], natural-based solutions (NBS) such as SUADS-WR address five of them. These challenges include UCC1 “restore and maintain the water cycle,” mainly through stormwater management; UCC2 “Treatment, recovery, and reuse of water and waste”; UCC3 “nutrient recovery and reuse” with a focus on nitrogen and phosphorus; UCC4 “Energy efficiency and recovery,” including mitigation of the urban heat island effect; and UCC5 “Building System Recovery,” related to the topic of regeneration of a built environment.

Thanks to the implementation of a method based on the daily water balance of the system and supported by hydro-informatics tools specifically designed for this purpose, the realization of a SUADS-WR design became viable. This method retains its applicability even in scenarios with limited climatic data, ensuring satisfactory accuracy and making it feasible for implementation in almost any region and country. However, there is still room for developing supplementary models and hydro-informatics tools, such as improving the SUADS-WR for urban flood mitigation. This future development must consider the guidelines for a precipitation event with a T-return period, the catchment area for a specific SUADS-WR design, and the implementation of the Internet of Things (IoT) to operate and control potential valve and pump systems. This will ensure the capacity to real-time mitigate excess water in the city’s storm sewage system.

5. Conclusions
The methods proposed in this study for determining irrigation depths in golf courses, as well as other urban green spaces, and for establishing dimensions for rainwater bioretention systems, are validated through a comparison between data from the experimental green and the estimated outcomes. In fact, both the estimated irrigation depth and percolation depth demonstrate consistency, yielding results that closely resemble the data acquired from the lysimeter of the experimental green.

The results of the annual water balance obtained in the experimental green show that the excess applied irrigation depth exceeds the precipitation depth of the location in some years. Therefore, the surplus irrigation water could be stored and reused to meet the irrigation demand when needed.

The Hargreaves–Samani method used in this study as an alternative method to estimate reference evapotranspiration produces reliable results for obtaining the irrigation depth. Therefore, the use of this method is recommended in sites where there is not enough information available for estimating evapotranspiration using the Penman–Monteith method.

The proposed methods and hydro-informatics tools facilitate the optimal determination of SUADS-WR design; harvested water volume for reuse; irrigation quantity and frequency to supply; water reuse percentage; and the potential for retention and reuse of leached fertilizers.

Based on the results obtained regarding the experimental amount of leached fertilizers measured in the case study, it is important to mention that having a SUADS-WR, as proposed in this work for the lawns of a golf course, will enable the protection of water
bodies from tons of nitrogen and phosphorus that are discharged and leached in golf courses without being utilized by the grass. These fertilizers could be harnessed through water reuse. It was demonstrated that with just a 300 mm height storage tank below the edaphic zone, it is enough to reduce water consumption and eliminate the negative impacts generated today by polluted water leaching into the aquifer.

SUADS-WR not only has the potential to address five urban circularity challenges, encompassing restoring and maintaining the water cycle, water reuse, nutrient recovery and reuse, reducing the urban heat island effect, and building system recovery, but it also tackles water scarcity by managing water demand and offering cultural services. These services include opportunities for physical activity, social interaction, and spaces for gathering and relaxation, ultimately contributing to the improved health and well-being of urban dwellers.


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