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Research article

Modelling the potential of rainwater harvesting to improve the sustainability of landscape and public garden irrigation

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ABSTRACT

Access to water for irrigating amenity landscape and public gardens is under intense pressure due to the rising competition for water between different sectors, exacerbated by increased drought risk and climate change. Rainwater harvesting (RWH) has the potential to reduce the economic impacts of restrictions on irrigation abstraction in dry years and to build resilience to future water shortages. This study investigated the hydrological viability of RWH for the landscape and public garden sector based on an analysis of five Royal Horticultural Society gardens. A RWH model was developed and combined with on-site observations, key informant interviews and GIS analyses, to estimate irrigation demands and the volumes of harvested rainfall for contrasting agro-climatic years. The results showed that gardens located in wetter regions and with low irrigation water demand to harvestable area ratio had a higher RWH potential and could almost exclusively rely on rainwater to meet irrigation demand, even in dry years. RWH potential is more limited for gardens in drier regions where they would require larger areas to harvest rainwater and for storage. Appropriately designed rainwater harvesting systems offer the potential to remove most of the risk of irrigation abstraction restrictions during dry years and associated impacts on amenity planting quality and visitor experience.

1. Introduction

Landscape and public gardens deliver multiple societal benefits through their positive impacts on human wellbeing and physical and mental health (Maller et al., 2006; de Bell et al., 2020), their economic contribution to tourism and employment (Croy et al., 2020), their environmental role in maintaining biodiversity (Moyle and Weiler, 2017) and providing green infrastructure and ecosystem services (Cameron and Blanusa, 2016). Most public gardens rely on public mains water and surface and groundwater abstraction for irrigation (Slack and Manning, 2020; Jackson, 2016). However, irrigation from these sources is often restricted during drought events, threatening the health of plants and trees, leading to economic and biodiversity losses (Jackson, 2016). Moreover, over abstraction is harmful to the environment (Defra, 2013) and mains water supplies are constrained in many regions (Hejazi, et al., 2014), highlighting the need for landscape and public gardens to access alternative water sources to reduce their vulnerability from future regulatory and climate risks (Gush et al., 2022).

Wurthmann (2019) reported that rainwater harvesting (RWH) could address residential landscape irrigation needs in Florida in a sustainable way if sufficient storage was available. Zhong et al. (2022) demonstrated in Arizona that RWH deployed at the city-scale could meet 32% of urban outdoor irrigation demand for 8 months in a wet year, which could lead to an annual saving of US$13.8 million. RWH could also be effectively used for urban agriculture based on a study in Rome that reported that 33% of urban gardens could be water neutral (water self-sufficient) for irrigation by harvesting rainfall from building rooftops and that the other gardens could meet 44% of their water needs, assuming high irrigation efficiency practices (Lupia et al., 2017).

The science literature confirms that RWH could be a promising solution to overcome the water challenges that landscape and amenity gardens are facing. However, from a RWH perspective, landscape and amenity gardens differ from urban settings in terms of their timing of irrigation demand, the relative importance of the harvestable area compared to water demand, and opportunities to collect and store rainwater. The aim of this research was therefore to assess the hydrological viability of RWH to meet irrigation demand at the landscape and public garden scale, drawing on case studies from five UK public gardens

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managed by the Royal Horticultural Society (RHS). The specific objectives were to critically review and assess the gardens' current RWH potential (volume of harvestable and storable rainwater compared to irrigation demand) for different agroclimatic years and to evaluate the hydrological feasibility of RWH to achieve water neutrality (for irrigation purposes).

2. Methodology

This study relied on a conceptual RWH model originally developed for soft fruit growers in England to evaluate the hydrological and water storage performance of RWH systems for protected cropping (Knox et al., 2021). In this study, that model was modified and used in combination with on-site observations and data, key informant interviews with RHS staff and GIS analyses to estimate the daily volume of rainwater harvested and daily irrigation demand, and to simulate the water balance in storage reservoirs under contrasting agroclimatic years (Fig. S1).

2.1. Study area

The study focused on five RHS gardens: Bridgewater (Greater Manchester), Hyde Hall (Essex), Harlow Carr (North Yorkshire), Rosemoor (Devon) and Wisley (Surrey). These are in contrasting agroclimatic regions, with annual average rainfall ranging between 1000–1250 mm at Rosemoor, 800–1000 mm at Bridgewater and Harlow Carr, and only 600–700 mm at Hyde Hall and Wisley (Met Office, 2022). Table 1 provides summary statistics for each garden in terms of area, water sources and soil types.

Small RWH and sustainable urban drainage systems contributing to irrigation already exist at Bridgewater and Wisley (RHS, 2021), but no RWH system is deployed at the garden scale. In this study, RWH potential was assessed without these existing systems, as their contribution to meeting the site's total irrigation demand had not been evaluated.

2.2. Data collection

Daily rainfall data from 1961 to 2015 for Wisley were retrieved from a local automatic weather station (51°18′39"N, 0°28′36"W, altitude 38 m) and for the other gardens, daily rainfall data for 1961 to 2012 were retrieved from CHESS, the Climate, Hydrology and Ecology research Support System explorer (UK Centre for Ecology & Hydrology; Robinson et al., 2015a), and for 2013 to 2015, from a 1 km gridded climatological dataset derived from the Met Office observed precipitation database (Tanguy et al., 2021). For the five gardens, for 1961 to 2012, daily potential evapotranspiration (PET) data assuming a well-watered grass as defined by the FAO (Allen et al., 1998) and computed using the Penman-Monteith equation (Monteith, 1965) were retrieved from the CHESS dataset Robinson et al. (2015b); For 2013 to 2015, daily PET data derived from the McGuinness-Bordne equation (Oudin, et al., 2005) were retrieved from the Met Office 5 km gridded climatological dataset (Tanguy et al., 2017).

Table 1
Site characteristics of RHS gardens.

Site	Area (ha)	Primary irrigation water source	Dominant soil type
Bridgewater	62	Groundwater	Clay loam
Hyde Hall	150	Reservoir	Clay loam
Harlow Carr	58	Mains water supply	Clay loam
Rosemoor	26	50% mains water supply – 50% river	Loam
Wisley	97	River borehole and mains water supply	Sandy loam

2.3. Model development

The conceptual RWH model operates on a daily time-step and is composed of three modules simulating (i) irrigation demand, (ii) rainwater harvesting, and (iii) water storage, which are briefly described below. Fig. 1 summarises the modelling workflow for each module.

2.3.1. Irrigation water demand module

The inability to simulate horticulture irrigation demand due to the complexity of spatial planting and lack of data on plant evapotranspiration properties led to the adoption of a reverse engineering approach, consisting of understanding how annual irrigation water demand (IWD) was influenced by climate. A curator interview revealed the typical irrigation depths applied at Wisley are determined using local soil moisture status. Therefore, an agroclimatic index termed 'annual maximum potential soil moisture deficit' ($PSMD_{max}$) was used to estimate the annual garden IWD, using a daily time-step (*i*) water balance, with rainfall (P, mm) as an input and PET (mm) as an output:

$$PSMD_i(mm) = \begin{cases} 0, if\ P_i \geq PSMD_{i-1} + PET_i \\ PSMD_{i-1} + PET_i - P_i, else \end{cases} \quad (1)$$

This index has been widely used in previous research to correlate agroclimate with irrigation needs (Knox et al., 2007) at various scales and locations (Rey, et al., 2016). The approach in this study was to compare the annual $PSMD_{max}$ distribution to the annual IWD distribution (Fig. S2). For each site, the daily PSMD was estimated for 1961 to 2015 and the maximum annual values probability plotted to create the $PSMD_{max}$ distributions. For the annual IWD distribution, monthly records of volumes abstracted from the river and borehole for irrigation between 2003 and 2015 at Wisley were retrieved. Based on previous research by Multsch et al. (2015) and Popova et al. (2012), it was assumed that the relationship between annual IWD and probability of non-exceedance (i.e. the probability that annual IWD is not greater than a given value) was linear. Therefore, only two points were selected from Wisley's historical data to create the distribution: one 'average' year value (corresponding to a 50% probability of non-exceedance) and one 'very dry' year value (corresponding to a 90% probability of non-exceedance). This approach was used only for RHS Wisley since irrigation records were available for this site. However, to estimate the equivalent value for the other gardens, the following equation was used:

$$IWD_{garden}(m^3) = IWD_{estimated} * \frac{IWD_{average,garden}}{IWD_{average,Wisley}} \quad (2)$$

where IWD_{garden} was the annual estimated IWD for a given site, $IWD_{estimated}$ was the annual estimated IWD at Wisley, $IWD_{average,\ garden}$ was the annual average volume of water used for horticulture at a given site and $IWD_{average,\ Wisley}$ was the annual average volume of water used for irrigation at Wisley. The two points used to create the IWD distribution site were calibrated independently for each site so that the mean of the annual IWD estimated by the model was equal to the average volume of water used for horticulture estimated by the RHS. The monthly distribution of the annual IWD was then determined by analysing historical abstraction records for Wisley. The analysis identified two significantly different patterns: one for 'dry' years (>70% probability of non-exceedance) and one for 'other' years. It was assumed that the observed patterns at Wisley were similar for the other sites, except for Harlow Carr where an interview with the site curator revealed a different pattern of irrigation demand. Finally, the daily irrigation demand was estimated by dividing the monthly demand by the number of days in each month.

2.3.2. Rainwater harvesting module

The model assumed that rainwater was collected from building roofs and then stored in a tank, and from waterbodies (e.g. lakes, ponds) receiving runoff from their drainage basin.

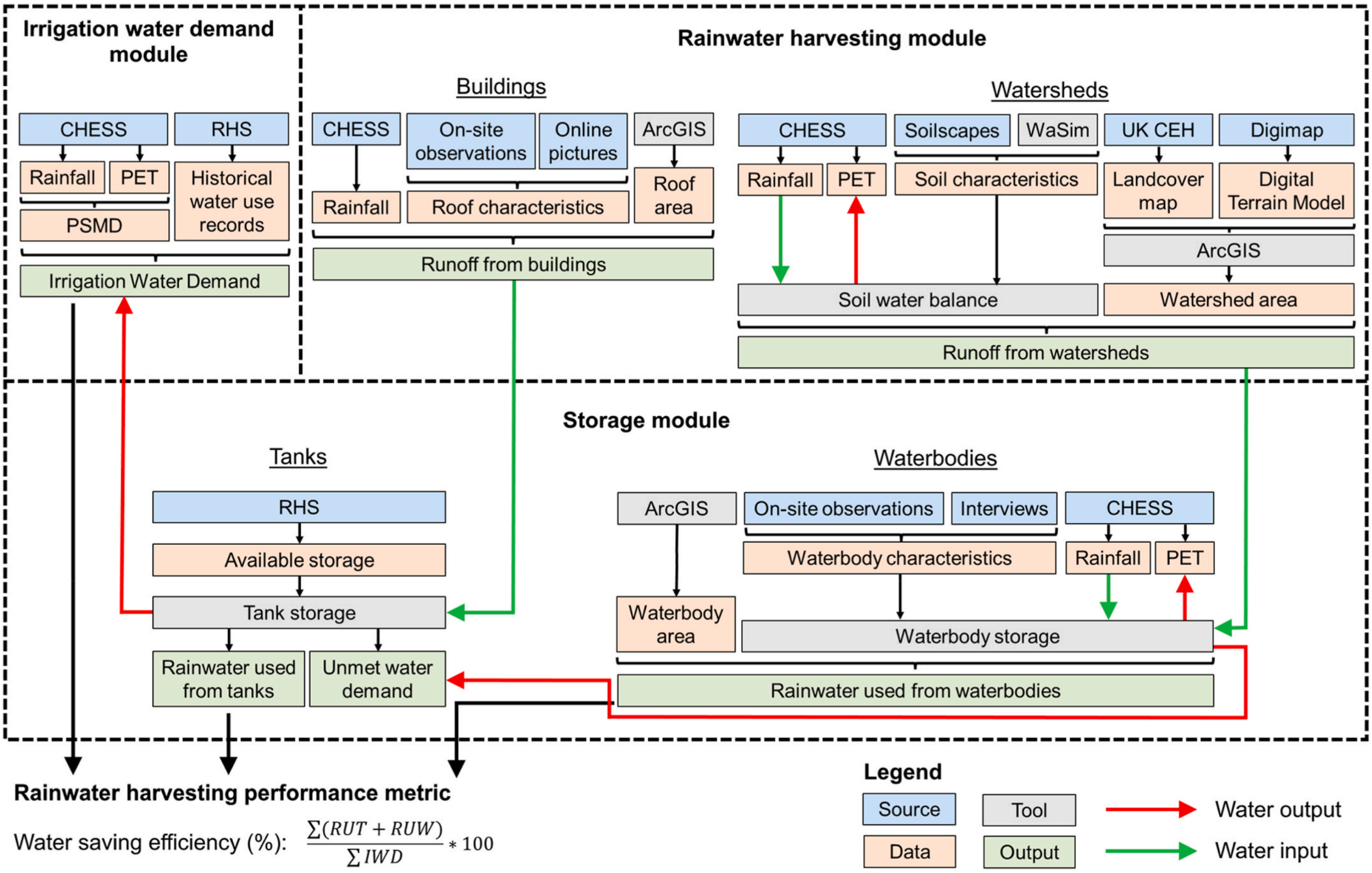

Fig. 1. Schematic representation of the RWH model workflow.

2.3.2.1. Building roofs. The approach to estimate the amount of rainwater collected from buildings roofs relied on two parameters: rainfall threshold (RT, mm), below which no runoff is produced, and the runoff coefficient (RC, dimensionless) which represents losses due to depressional storage, wind effects and/or evaporation (Knox et al., 2021). Therefore, the volume of runoff produced (R, m^3) from a given roof area (A, m^2) during the day i was estimated:

$$R_i(\mathrm{m}^3) = \begin{cases} 0, if\ P_i < RT \\ \frac{(P_i - RT)}{1,000} * RC * A, else \end{cases} \quad (3)$$

Ragab et al. (2003) demonstrated that RT and the RC were also influenced by roof slope (with a higher RC and a lower RT for a steeper roof) and roof orientation relative to the prevailing wind direction (with a lower RC and a lower RT for a prevailing wind facing roof). Roof slopes were assessed visually on-site at Wisley and using online imagery (Google Maps) for the other sites. Three types of slopes were defined: 'flat roof', 'shallow roof' (<45°) and 'steep roof' (≥45°). The prevailing wind direction was determined for each site by creating wind rose diagrams using the MIDAS (Met Office Integrated Data Archive System) open dataset retrieved from the CEDA Archive website (Met Office, 2019). Information on the weather stations used are given in Supplementary Information (Table S1).

Three building orientations to the prevailing wind direction were considered: 'facing' (roof is roughly perpendicular to wind direction), 'not facing' (roof is roughly aligned with wind direction) and 'in between'. The orientation of each building was defined by comparing the prevailing wind direction from the rose diagrams with satellite imagery. Ragab et al. (2003) also reported on the seasonal influence on the RC, with higher values in winter than in summer. Table 2 summarises the RT and RC values for different roof slopes, building orientations, and seasonal periods.

Roof values were derived from Ragab et al. (2003) with 'glasshouse' representing any building with a glass roof or a polytunnel. 'Glasshouse' RT and winter RC values for a 'not facing' buildings were determined by interviews with farm businesses by Knox et al. (2021) and not by experimental observations, explaining why these (especially RT) values were higher than the other roof values. Other 'glasshouse' characteristics were determined by analyzing how the building orientation and the seasonal period influence RT and RC values of buildings roofs (Ragab et al., 2003). To estimate the total area of each roof type (defined by slope and orientation for buildings and by orientation for glasshouses)

Table 2
Rainfall threshold and runoff coefficient values selected for the different slopes and orientations (F: Facing, IB: In between, NF: Not facing).

Variable	Roof slope							Glasshouse		
	Flat	Shallow			Steep					
		F	IB	NF	F	IB	NF	F	IB	NF
Rainfall threshold (RT) (mm)	0.70	0.60	0.65	0.70	0.50	0.55	0.60	1.67	1.83	2.00
Runoff coefficient (RC) (May-Oct)	0.60	0.65	0.67	0.70	0.70	0.72	0.75	0.70	0.75	0.80
Runoff coefficient (RC) (Nov-April)	0.70	0.75	0.77	0.80	0.90	0.92	0.95	0.80	0.85	0.90

within each site, the ArcGIS Geodesic Area Measurement tool was used.

2.3.2.2. Watershed. For precipitation falling over an impermeable area within a watershed (excluding roof area), the same approach as used for building roofs was adopted, but with a RT value of 1.5 mm (Hingray et al., 2009) and a RC value of 0.8 (CivilWeb Spreadsheets). However, for rainfall falling over the watershed on vegetated and bare soil areas, an alternative approach was developed as the volume of runoff generated by a soil depends on its antecedent wetness conditions. Therefore, a daily soil water balance approach was used to model soil water fluxes in the top 150 mm layer. The only input was net precipitation (NP, mm), computed for each day *i* as follows:

$$NP_i\ (mm) = (1 - INT) * P_i \tag{4}$$

where INT was the fraction of precipitation intercepted before reaching the soil, which depends on land cover. Three land cover types were considered: 'grassland' (i.e. lawns, meadows), 'woodland' (including orchards), and 'mixed planting' (i.e. shrubs, border/herbaceous perennial plantings). Soil water losses were via three routes – evapotranspiration, drainage to a sub layer, or overland runoff – depending on the soil moisture content (θ) and soil characteristics, and three parameters: 'soil saturation' (SAT), 'field capacity' (FC) and 'permanent wilting point' (PWP), corresponding to threshold values for soil moisture content. When the soil moisture content reached saturation, any excess rainfall could not infiltrate the soil and produced 'potential runoff' (PR, mm). Part of this PR was intercepted in 'depressional storage' (DS, mm), so the 'effective runoff' (ER, mm) represented the difference between PR and DS. Fig. 2 shows how soil moisture (S, mm) and DS were computed on day *i* in the soil water balance model and Table 3 shows the interception and depressional storage values used for each land cover type. The drainage to sub layer (Q, mm) was calculated on day *i* (Raes, 2002):

$$Q_i(mm) = \tau * (SAT - FC) * \frac{e^{\theta_i - FC} - 1}{e^{SAT-FC} - 1} * 150\ mm \tag{5}$$

where τ was the drainage coefficient (dimensionless) which was dependent on soil texture. When the soil moisture content went below FC, it was assumed that no more water would drain to the sub layer. Thus, water could leave the soil only by evapotranspiration from plants, until the soil moisture content reached the PWP value, where all available water had been used. The final volume of runoff produced by the soil was the product of ER and watershed area for the corresponding land cover.

To ensure the model produced a realistic response in terms of timing and volume of runoff and that the periods of drought and flood were accurately represented, soil characteristics (SAT, FC, PWP and τ) were calibrated for three locally representative soil textures (clay loam, loam and sandy loam) by comparing the model outputs for a 'grassland' land cover to the equivalent outputs from WaSim, a daily water balance model developed by Hess and Counsell (2000). Information on WaSim was configured to run the simulations is given in Supplementary Information (Table S2).

The runoff values from WaSim were estimated using the SCS Curve Number approach (Hess et al., 2000), which considers losses due to rainfall interception, soil infiltration, and depressional storage (Cronshey, et al., 1986). Therefore, the WaSim outputs were compared to ER values generated by the RWH model. To avoid any influence from the WaSim initial conditions in the outputs, a 7-year initialization period for the WaSim model was set up based on observations from multiple simulations with different run parameters. Data from the two models were compared from 1968 to 1987 for calibration and from 1995 to 2015 for validation. The criteria to assess model accuracy was the total amount of

Table 3
Interception and depressional storage values used for each land cover type.

Land cover	Interception	Depressional storage (mm)	References
Mixed planting	0.15	5.0	Kozak et al. (2006); Hingray et al. (2009)
Grassland	0.05	3.0	Ochoa-Sanchez et al., 2018; Hingray et al. (2009)
Woodland	0.30	7.5	Aussenac and Boulangeat (1980); Pearce et al. (1980); Hingray et al. (2009)

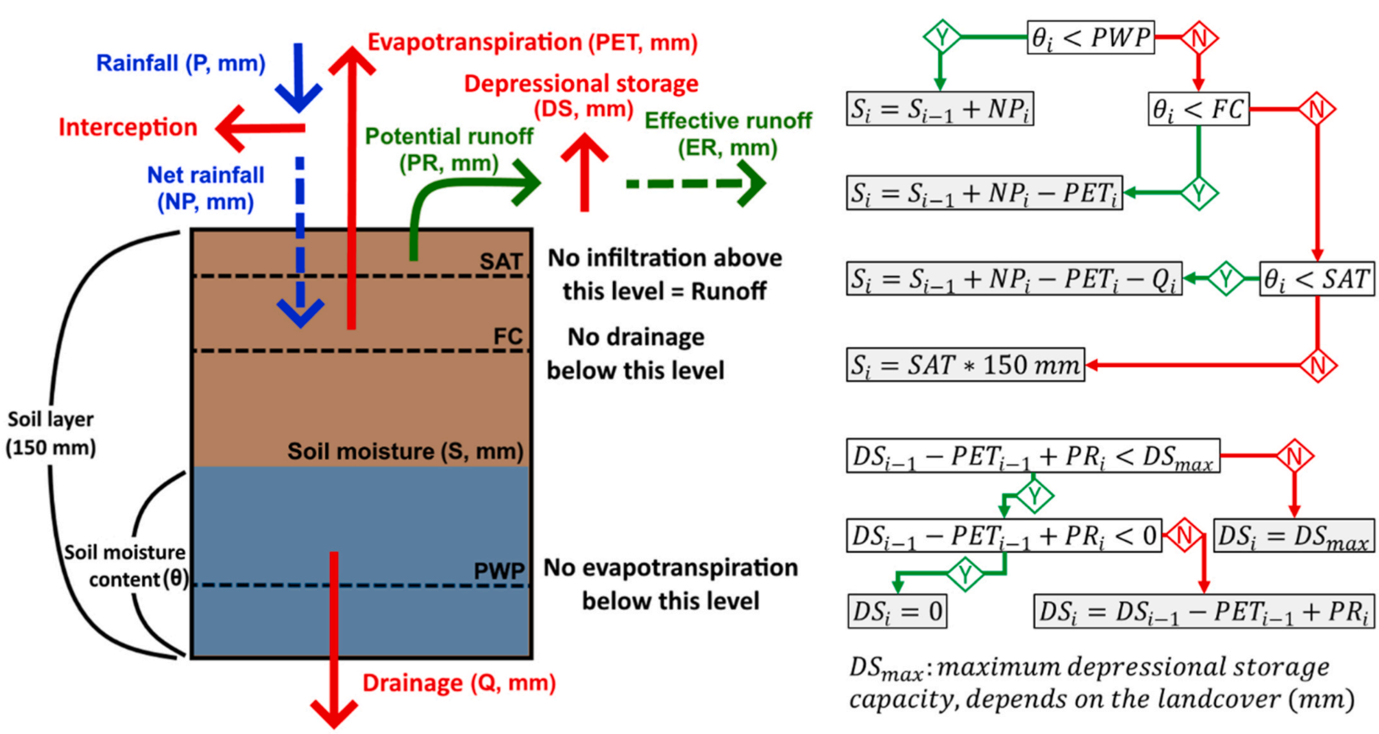

Fig. 2. Flowchart and schematic representation of the conceptual soil water balance.

runoff produced during the run period and its monthly and annual distribution. Soil characteristics values selected after calibration for each soil type are given in Supplementary Information (Table S3).

The final step was to determine the watershed areas for the three land cover types at each garden site. To delineate waterbody drainage basins in ArcGIS, guidelines developed by Ballatore (2015) were followed. The 1:10,000 Digital Terrain Model was retrieved from the EDINA Digimap Ordnance Survey Service (2022) for each site. The 10 m grid pixel classified land cover map (2020) produced by the UK Centre for Ecology & Hydrology was then used to determine the area of each land cover type within each watershed. As the model considered only four land cover types, the UKCEH classification was simplified (Table S4). A summary of the harvestable surface area by type and site is given in Supplementary Information (Table S5).

2.3.3. Storage module

The volume of rainwater stored within a tank on day *i* was estimated using equations developed by Knox et al. (2021). Fig. S3 schematically represents how the tank storage module was implemented in the RWH model. An estimated ST_{max} value (i.e. estimated current capacity to store rainwater) of 600 m^3 was used for Bridgewater, 225 m^3 for Harlow Carr, 0 m^3 for Hyde Hall, 150 m^3 for Rosemoor and 820 m^3 for Wisley, based on RHS data. Tanks were assumed to be full at the beginning of the simulation. The approach for estimating the volume of rainwater in waterbodies was different to the tanks as open water evaporation needs to be considered. Moreover, as ornamental water features support unique ecosystems, they cannot be managed and drawn down in the same way as conventional irrigation storage tanks. A threshold water level was therefore defined below which no further water could be abstracted. Waterbodies were assumed to be used only when the IWD was not met from rainwater tanks (i.e. $RUT_i < IWD_i$). Fig. S4 shows the equations for simulating the water level in waterbodies on day *i*. The variable SW did not represent the actual waterbody water level, because this information was not available would have required modelling each waterbody independently. This variable represented the change in waterbody water level compared to their initial level at the beginning of the simulation. Therefore, the starting value of SW was set a 0 mm for each garden. The variable SW_{max} was set at 500 mm according to on-site observations and SW_{min} at −350 mm based on interviews with RHS staff. R^W was estimated as the volume of runoff from the watershed divided by waterbody area, and UWD as the difference between IWD and RUT, divided by waterbody area. Since Hyde Hall was reported to be water neutral (for irrigation purposes) with a reservoir capacity of 45,460 m^3 (RHS, 2021), the SW_{min} for this garden was set to −5500 mm, corresponding to the reservoir volume divided by its area.

3. Results

3.1. Rainwater harvesting potential of RHS gardens

Fig. 3 shows the mean monthly rainfall at each site in relation to mean monthly IWD. Hyde Hall and Wisley receive a significantly lower amount of rainfall compared to other gardens during the irrigation season. Fig. S5 shows the variation in estimated annual IWD for each site with Hyde Hall and Wisley having a much higher annual IWD compared to the other sites. Fig. 4 shows the effective runoff coefficient (i.e. ratio between the volume of effective runoff produced and volume of gross rainfall over the harvested area) and the total and effective harvested area (i.e. the area that with an effective runoff coefficient of 1.0 would deliver the effective runoff volume) for each site. Effective harvested area is a useful metric that allows comparison of the contribution of each surface type to the production of runoff. It is computed by multiplying the effective runoff coefficient by the harvested area.

Two management scenarios were considered, (i) only harvested rainwater from storage tanks is used for garden irrigation, and (ii) rainwater from RWH tanks and other waterbodies are used for irrigation. Fig. 5 shows the 'water saving efficiency' (WSE) distributions for

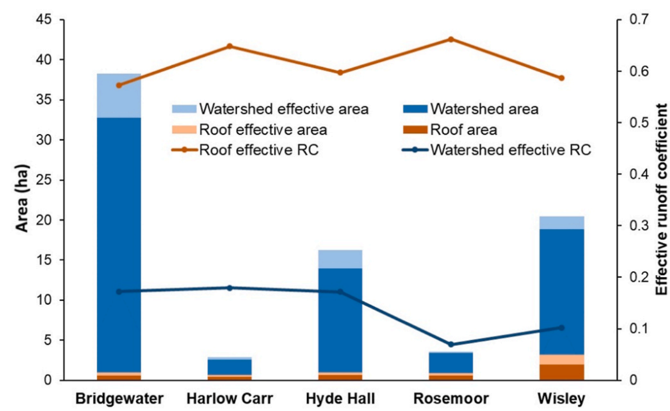

Fig. 4. Total and effective harvested area (roof and watershed) of each site (stacked bars).

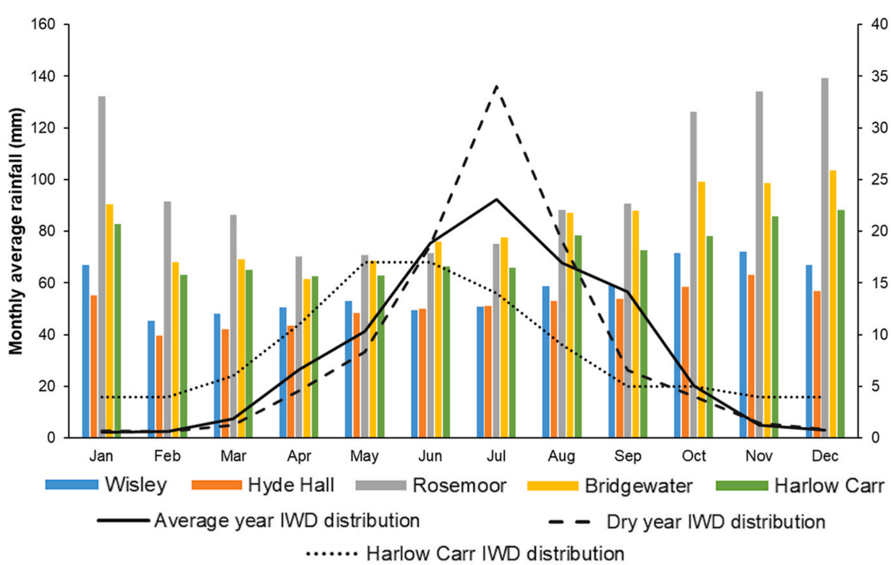

Fig. 3. Mean monthly rainfall at each site in relation to mean monthly IWD distribution.

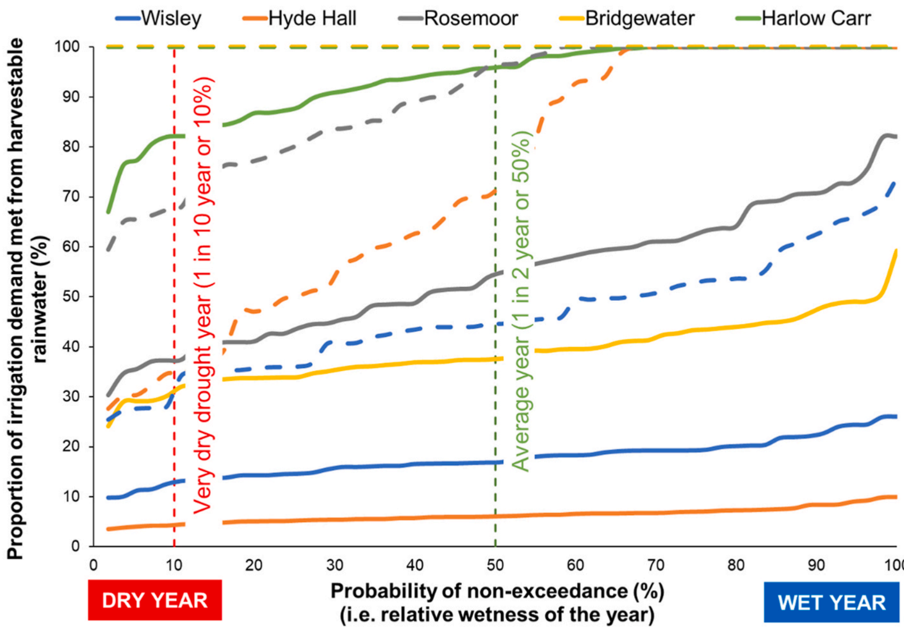

Fig. 5. Distribution of water saving efficiency for scenario 1: storage tanks only (solid lines) and scenario 2: tanks and waterbodies (dashed lines) for each site.

these two scenarios. The WSE represents the percentage of the annual IWD met from the annual volume of rainwater harvested (RUT + RUW). In the first scenario, Wisley and Hyde Hall have a low WSE, and Harlow Carr is the only garden that could still meet most of its IWD (*c*80%) from rainwater during a dry year. An increase in RWH potential, as shown by the higher WSE values in the distributions, is observed under scenario 2 where Bridgewater could rely entirely on RWH for irrigation while it could only meet 60% of its IWD for the wettest years under scenario 1. However, RWH would not be sufficient to meet the IWD for most years at Rosemoor and Hyde Hall and would only cover 70% of the IWD at Wisley even in the wettest years.

3.2. *Rainwater harvesting challenges in attaining water neutrality*

The infrastructural option to improve RWH potential was to increase storage capacity. For this, the optimum ST_{max} value (i.e. the ST_{max} value above which no significant improvement in RWH performance is observed) was estimated for each site by running multiple simulations. Fig. 6 shows optimal RWH tank capacities and their impact on RWH potential, for different agroclimatic years, assuming scenario 1. Increasing storage capacity showed little influence on RWH performance under scenario 2 (with relative increases in the WSE ranging from 0 to 12%, except for Rosemoor where the WSE in dry years was projected to increase by 47%). Using Wisley as an example, Fig. S6 shows that the additional volume of runoff produced from roofs that could be harvested with additional storage, represented by the current tank overflow, is limited. Therefore, increasing storage capacity has limited potential to improve RWH efficiency for most gardens and is not sufficient to attain water neutrality even in scenario 2.

4. Discussion

The modelling outputs showed contrasting results for RWH performance between each site, mainly due to heterogeneities in the individual garden characteristics. For example, both Hyde Hall and Wisley are in dry regions and receive relatively low rainfall during periods of peak irrigation demand, meaning they have limited volumes of rainwater available to harvest when it is most needed (Fig. 3). These gardens also have a higher IWD (Fig. S5) due to their lower annual rainfall, more drought sensitive soils, and larger irrigated areas (Table 1). Bridgewater and Wisley can harvest rainwater over a much larger area than Rosemoor or Harlow Carr (Fig. 4) and have more storage capacity than the

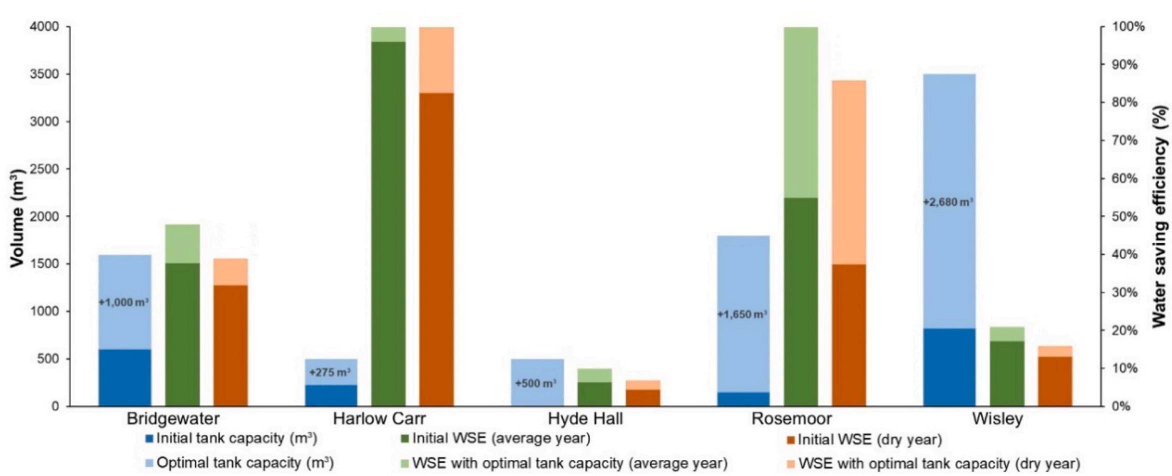

Fig. 6. Optimal storage tank capacities (m^3) and their relative impact on WSE at each site.

other gardens.

This variety of characteristics enables key factors that influence RWH potential to be identified. Fig. S7 shows the gardens relative rankings according to their RWH potential and characteristics with the 'best case' ranked first and the 'worst case' ranked fifth. The 'best case' for RWH potential refers to the highest WSE distribution (Fig. 5). For site characteristics, this refers to the highest value among the gardens for the average amount of summer rainfall, harvested area, and storage capacity, and refers to the lowest value for the IWD, the IWD in relation to harvested area and the IWD in relation to storage capacity. If the ranking of gardens for a given characteristic follows the WSE-based ranking, this means that this characteristic is an influencing factor for a gardens' RWH potential.

Fig. S7 confirms that summer rainfall is relatively well correlated with RWH potential (i.e. a higher summer rainfall corresponds to a higher RWH potential) and that the IWD is strongly correlated with RWH potential (i.e. a lower IWD means a higher RWH potential). Similar observations were made by Wurthmann (2019) in a study on RWH for residential outdoor irrigation, which reported on the importance of taking precipitation patterns and landscape irrigation needs into account. Harvested area and storage capacity showed no correlation with RWH potential, but when related to IWD, storage capacity showed a good correlation with RWH potential and harvested area and seems to be the most suitable characteristic to determine RWH potential. In a study on RWH to address outdoor irrigation at the city-scale, Zhong et al. (2022) concluded that different rainwater storage sizes and variations in catchment area were key factors in the efficiency of RWH systems.

This study has also highlighted the potential for using waterbodies to collect and store rainwater for irrigation in public gardens, especially at Bridgewater, considering the relative importance of watershed effective area compared to roof effective area (Fig. 4) and the impact that their exploitation has on WSE (Fig. 5). With waterbodies and their watersheds as key factors for RWH in public gardens, soil texture becomes another important characteristic that influences RWH potential. Our results showed that gardens with lower infiltration rate soils (e.g. clay loam) have a significantly higher watershed effective runoff coefficient compared to gardens with loamy or sandy soils (Fig. 4).

The difference in roof characteristics between the gardens also impacted on RWH performance: Harlow Carr and Rosemoor have a significantly higher roof effective runoff coefficient compared to the other sites (Fig. 4) because of the dominance of steep roofs in their building composition (45% and 34%, respectively), while the dominant roof type at Bridgewater was flat (62%) and shallow at Hyde Hall (64%). At Wisley, 26% of building roofs were steep, compared to only 5% at Bridgewater and 14% at Hyde Hall, but the roof effective runoff coefficients for these three gardens was quite similar because of the importance of glasshouses at Wisley (44% of building composition) which were modelled with a much higher rainfall threshold value than for the other roof types. While the RT values for other roof types were determined from experimental observations, the glasshouse RT value came from interviews with farm businesses, potentially underestimating RWH potential for gardens where glasshouses are important (e.g. Wisley). Further research is required on the water fluxes for glasshouses and polytunnels.

Irrespective of management scenario, the WSE showed a high sensitivity to climate conditions. Rainwater could supply a significant part of the annual IWD even in the driest years but would not be sufficient for some gardens to attain water neutrality (Fig. 5). Therefore, new infrastructure would be needed to increase RWH potential. The challenge for water neutrality (for irrigation purposes) is to maximise the benefit of each rainfall event. This requires ensuring that sufficient storage capacity is available to avoid overflow during intense summer storms. Fig. 6 shows that increasing storage capacity would enable Harlow Carr and Rosemoor to rely entirely on RWH to address their IWD, even in dry years. This would also significantly improve the RWH potential at the other gardens, but not sufficient to reach water neutrality. The issue is that insufficient runoff is produced from the rooved areas, due to lower rainfall (Fig. S6). This highlights the limited impact of increasing storage capacity as a solution to improve RWH potential. Moreover, increasing storage capacities to their optimal volume might also be challenging for gardens. This would require additional 'land take' on an area already occupied by valuable horticultural planting as well as causing aesthetic issues, implying the need to build underground tanks, thus increasing investment costs. There is a need to consider alternate infrastructure that would facilitate harvesting rainwater across larger areas to attain water neutrality. For example, one option would be to cover car parking bays to collect additional rainwater runoff. This would also enable solar panels to be installed to generate renewable energy to support pumping water collected from the RWH systems to the irrigated areas.

Improving RWH potential for public gardens is also relevant in the context of improving stormwater management, by understanding where and when runoff is produced, its flow pathways, and how best to collect and divert floodwater to storage reservoirs or tanks. To improve runoff management, passive RWH systems could be developed in landscape and public gardens. These consist of slowing water from a catchment area down to the irrigated area and encouraging soil infiltration using berms and swales, infiltration basins, terraces, or dry streambeds (Daily and Wilkins, 2012). Passive RWH has shown good potential to address irrigation needs when used in conjunction with active RWH (Zhong et al., 2022) while enhancing landscaping and garden aesthetics. To de-risk gardens from future water regulatory and climate risks, using greywater as an alternative source for irrigation could also be considered. Greywater irrigation has been adopted worldwide (Turner et al., 2013) and has potential for landscape and public gardens. For example, the average internal water use at RHS gardens ranges between 4500 and 15,000 m^3/year but would require treatment to avoid changing soil characteristics and harming plants (Gross et al., 2005) with water quality assessed and monitored carefully at each site (Mohamed et al., 2013).

Considering its high potential and reliability, RWH is likely to be adopted by landscape and public gardens in the future. This will be even more acute in countries such as the UK where deployment of water saving technologies are supported by policies to address challenges linked to water resources availability (Water, 2016) and where the use of rainwater is not regulated and does not require an abstraction licence (EA, 2021). The RHS has committed to increasing RWH across all its sites in its sustainability strategy (RHS, 2021). Moreover, RWH can be implemented aesthetically as part of an integrated plan (i.e. with multi-purpose infrastructure) using passive RWH systems and waterbodies as ornamental features. Although climate change will induce an increase in frequency and severity of extreme events such as droughts and floods (Toosi et al., 2020; Bekele et al., 2019), the results showed that RWH can help landscape and public gardens to cope better with dry spells by providing an emergency water source when abstraction and public mains water are constrained and can also be helpful for flood management. Indeed, Palla and Gnecco (2022) demonstrated that domestic RWH catchment-scale applications could be effective in supporting urban flood management when sufficient storage is available, and Xu et al. (2020) demonstrated that this could be enhanced with real time control of RWH tanks combined with long-term rainfall forecasts. Further research needs to be conducted to assess RWH potential in gardens for flood risk management.

Previous research has also demonstrated that RWH can be beneficial for the environment due to the reduction in energy use and greenhouse gas emissions compared to relying on treated mains water supply (de Sá Silva et al., 2022) and the reduction in direct abstraction (Campisano et al., 2017). However, at the residential scale, Rashid et al. (2016) demonstrated that by relying on pumps to manage water and energy savings and to reduce runoff and pollutant loads, the negative environmental impacts could actually be higher for developments with RWH systems compared to those without. There is a need for further research to assess the environmental impacts of RWH and energy trade-offs in public gardens using a life cycle analysis approach as pumps are inevitably needed to move water between storage facilities and irrigated areas.

Rainwater quality also needs to be considered as runoff from roofs can be altered by roof material, atmospheric and precipitation deposition, acid rain, gutter corrosion, or faecal contamination (Campisano et al., 2017). However, studies have shown that the overall quality of roof runoff is generally satisfactory (Rahman et al., 2014; Pathak and Heijnen, n. d.) for growing plants (Tomer, 2005; Ayers and Westcot, 1985). The main concern is for runoff from watersheds, which can transport plant diseases such as ramorum dieback, caused by *Phytophthora ramorum*, which causes damage to a wide range of plant species (Forest Research; Royal Horticultural Society, 2021). Therefore, harvested ground-based runoff needs to be treated before use if the presence of such pathogens is suspected.

Finally, it is important to recognise how certain assumptions made in this study could influence the results and their interpretation. The relationship between the annual IWD and probability of non-exceedance was assumed to be linear based on studies by Multsch et al. (2015) and Popova et al. (2012), but this is only acceptable for probabilities of non-exceedance ranging from 0.1 to 0.9. The RC values are usually calculated over extended periods rather than on daily basis, so they should also assess the impacts of depressional storage on runoff production as with the RT. The model used both RC and RT which may have over-estimated the impacts of depressional storage and under-estimated the volume of runoff harvested. The model also assumed that all runoff was is caused by saturation-excess runoff and ignored runoff due to the intensity of rainfall. The drainage systems at the RHS gardens can also prevent runoff from the watersheds reaching the waterbodies. However, only overland flow was considered in the waterbody balance, while interflow or groundwater flows could also recharge or empty the system, depending on reservoir type (lined or unlined) and local hydrogeology. Finally, the waterbodies might also not be as exploitable as they were assumed, because of the need to maintain water levels for aesthetic reasons or because of declining water quality impacts on aquatic dependent ecosystems.

5. Conclusions

This study assessed the hydrological viability of RWH to address irrigation demands within landscape and public gardens using a series of contrasting case studies. Analyses revealed that RWH potential varies widely due to differences in site characteristics, the presence of permeable and impermeable surfaces, and climate variability. Overall, harvested rainwater could provide a valuable additional water source for irrigation that could significantly reduce the vulnerability of nationally important gardens and visitor attractions due to abstraction restrictions in dry years. For gardens that are unable to fully meet their irrigation needs from harvested rainwater, their RWH potential could be increased by landscaping to facilitate passive RWH or by exploiting waterbodies to store rainwater from a much wider catchment area. Whilst the widespread adoption of RWH will also require assessment of economic viability, it does offer the potential of delivering multiple additional benefits including reduced downstream flood risks, and lower energy-related emissions.

Credit author statement

Jacque: Conceptualisation, methodology, data curation, formal analysis, writing - original draft, writing - review and editing. Knox: Funding acquisition, project supervision, conceptualisation, writing - original draft, writing - review and editing. Gush: Resources, methodology, writing - original draft. Holman: Conceptualisation, methodology, writing - original draft.

Data availability statement

Data supporting this study are included within the article and/or supporting materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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