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Allotments in the Future: Building Resilience to Climate Change through Improved Site Design and Efficient Water Practices

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Abstract: In recent years, there has been a resurgence in the popularity of allotments and home-grown food in the UK. This interest is likely to increase as people become more aware of the health benefits of spending time outdoors. Climate projections for the UK indicate that over the next 20 years, winters will become warmer and wetter, and the summers hotter and drier. Most UK allotments and community gardens are a collection of individual plots whose holders are free to manage them as they wish, within site rules. The efficacy of individual efforts to collect and store rainwater is often limited as most allotment sites were laid out when water practices were a secondary consideration. Our research, which included visiting allotment sites and reviewing growing practices, suggests that grouping plots and sharing water facilities could enable plot holders to store sufficient water to meet anticipated demand for thirty rain-free days in midsummer. This combined with growing practices that improve soil moisture capacity and water use efficiency will provide effective mitigation against climate change.

Keywords: allotment; climate change; sustainability; water efficiency; water harvesting; water storage

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1. Introduction

Allotment gardening has a long history in the UK and has gone in and out of popularity over the last 250 years. Social unrest among rural labourers who had nowhere to grow food for their families, following the enclosure of common fields in the 1700 and 1800s, lead to the creation of the first allotments [1]. The importance of allotments and private gardens in producing food during both the First and Second World Wars, when 1,500,000 plots produced over 20 million tons of food is well-documented [1]. The 'Dig for Victory' campaign, during World War 2, [1,2] was vital to ensure the health of the population, during and after the war, when food was rationed. Post-1960, an overall decline in the popularity of vegetable growing, combined with pressure for land within or on the outskirts of settlements for housing and business development, led many private owners, such as the Church of England and British Rail, as well as some local authorities to sell off allotment sites [1].

Over the last 25 years, there has been a resurgence in the popularity of allotments and home-grown food in the UK. There are many factors behind this, including concerns over the environmental costs of food transport and packaging [3] and the use of chemicals in food production [4], an interest in fresh home-grown produce [5], an awareness of the physical, mental and social benefits of being out of doors [6] and a desire to become part of a community [7]. Recent studies have demonstrated the potential benefits of allotment growing to improve food security [8]. During the 2020 COVID-19 pandemic, allotment growers supported one another by sharing produce with those who were struggling financially [2]. Concerns regarding the security of food supply chains following the decision of the UK to leave the European Union [9] have led to suggestions that increasing 'urban

greenspaces' may provide a partial solution to improving food security [8]. The water footprint of the 13.5 billion kg vegetables imported to the UK each year, is around 560 million m^3 (from cultivation and preparation); three-quarters of these vegetables come from countries where water supplies are limited [9,10]. Brazil, Bolivia, Ecuador, South Africa, Egypt, Morocco and India, all of which are considered highly vulnerable to the effects of climate change, each supply 5–10% of UK fruit and vegetables [11]. Increasing the amount of UK grown food would help to reduce this water imbalance. The positive benefits of increasing urban greenspaces, through the development of community gardens and allotments [12] include improved mental health and wellbeing [6,13,14]. According to the National Allotment Society (NSALG), the opportunity to visit an allotment throughout the COVID-19 pandemic provided many people with the ability to remain both physically active and mentally supported by the allotment growing community [15].

In 1996, in the UK, there were on average four people waiting for every 100 allotment plots, but by 2012 around 87,000 people were on waiting lists for just over 152,000 statutory plots managed by principal local authorities; the equivalent of 57 people waiting for every 100 plots [16]. In 2019, there were 10,435 allotment sites in Great Britain, covering an area of 7920 hectares (79.2 km^2), 0.45% of urban green spaces [17]. The United Nations Sustainable Cities Programme recognizes that sustainable food production has an important role in reducing the environmental impact of urban development, in promoting environmentally friendly lifestyles and in providing a pathway out of poverty [18]. This ambition has been adopted by many councils in the UK: for example, Bristol City Council's Allotment Strategy mission statement [19] is *'To work towards the vision of a sustainable Bristol through maximising the participation of its citizens in allotment gardening by the improvement of allotment sites and their management, and through the promotion of the benefits and enjoyment of allotments and food growing.'* In Bristol, during March 2020, only 521 of 3920 council managed plots were vacant and 5083 people were on waiting lists [19]. The Allotments Acts (1908) state that an allotment authority must consider providing allotments where there are six people or more requesting to rent allotments [1].

There is clearly a demand for new allotment sites. There is also a shortage of housing in the UK. In 2020, a House of Commons research briefing indicated that 337,000 new homes are needed [20]. In theory, local authorities could provide new allotment sites through the use of Section 106 planning obligations [21], so that each new housing development had a community garden or growing area included. Thus, new allotment sites would be close to residential areas and easily accessible to those who do not have access to cars or public transport.

There are many different types of allotment site and community garden. These range from semi-commercial 'shared harvest' schemes, such as the Sims Hill Shared Harvest group in Bristol [22], to garden squares [23] and small community flower beds that may only be a few meters square. However, the traditional allotment garden consists of several 250 m^2 plots, often laid out in more or less straight rows (Figure 1) [15].

Water use is often one of the largest expenditures on an allotment site [24]. Some sites have water supplied directly from the mains while others rely on incident, or collected, rainwater. Even when mains water is included in the rent charged for an allotment plot, the amount of water available to each plot holder is limited. The number of water troughs or taps are usually limited; there can be tensions between plot holders who use little water and those perceived as using more than their fair share and people whose plots are some distance from the tap may have to carry water to their plot. A hosepipe can use 600–1000 L of water in just one hour; this is more than the average household uses in an entire day [25]. On many allotment sites, hosepipe watering of crops is not allowed, but hoses can be used to fill up water butts or dipping tanks. The NSALG has, for many years, encouraged plot holders to (predominantly) use rainwater, and many growers consider that rainwater is better for plants than tap water [26,27]. Rainwater can be collected from the roofs of sheds, greenhouses and communal buildings but not all sites allow plot holders to put up buildings.



Figure 1. Aerial view of a typical allotment site with rectangular beds. Photograph courtesy Unsplash (https://unsplash.com/photos/ETAKnrWhbCs, accessed on 23 December 2020).

The UK climate change projections (UKCP09 and UKCP18) predict that within the next twenty to thirty years the UK will experience warmer and wetter winters and hotter drier summers [28]. Between 1961 and 2015, average air temperatures in Great Britain have risen by 0.20 ± 0.13 °C decade^{-1} and evapotranspiration by 0.87 ± 0.55 mm yr^{-1} yr^{-1} [29]. In the Bristol region by 2050s, temperatures may be 1.9 °C higher in winter and 2.4 °C higher in summer; summer rainfall is predicted to decrease by 14% compared to the 1961–1990 average [30] (Table 1).

Table 1. Likely changes in winter and summer rainfall and temperature in the Bristol region, compared with the 1961–1990 average, based on the UKCP09 climate change scenarios. Low emissions: a decrease in the rate of greenhouse gas emissions. Medium emissions: the same rate of emission of greenhouse gases as at present. High emissions: four times increase over the current rate of greenhouse gas emissions. Data taken from Afzal and Ragab (2019) [30].

	Time Period	Low Emissions		Medium Emissions		High Emissions	
		Winter	Summer	Winter	Summer	Winter	Summer
Change in precipitation (%)	2020s	4.7	−6.7	5.7	−7.52	6.1	−8.16
	2050s	10.3	−9.5	17.24	−14	15.7	−20
	2080s	17.3	−15.7	22.1	−20	23	−28
Change in temperature (°C)	2020s	1.1	1.61	1.27	1.72	1.3	1.5
	2050s	1.7	2.32	1.89	2.4	1.9	3
	2080s	2.1	3.08	2.6	3.6	3	4.5

Higher summer temperatures will increase the amount of water lost by evapotranspiration and are likely to increase demand for water. Any reduction in summer rainfall will increase pressure on existing water supplies not just for gardening but also for public water supply and recreation.

Irrigation and water availability are important concerns for many gardeners. A Google search, on 15 December 2020, using 'watering allotments' generated 317,000 results. In

the UK, gardening organizations and the government [16,31–33] publish information and guidance for gardeners about which plants to grow in different situations and the most effective way to utilize water (File S1). These all highlight the importance of collecting, storing and using water effectively. Collecting and storing water during the winter when, in the UK, rainfall normally exceeds water use will become even more important in the future because summer rainfall is predicted to decrease (Table 1) [28,30]. However, the way in which allotment sites are traditionally arranged and managed does not usually support water collection and storage or help growers to use water efficiently because in many cases, water storage and water use efficiency was a secondary concern when the allotment sites were created. Growers will also need to prepare for periods of intense rainfall in summer [28], this might include avoiding exposed soils on sloping plots, staking fragile plants and selecting plants or varieties that are more heat or drought tolerant. There are many different and complementary ways for gardeners to achieve resilience to predicted changes in conditions: improving water use efficiency, rainwater collection and storage, cultivation methods to improve soil water holding capacity, and designing the plot and site layout to minimize run-off and improve water infiltration.

We asked how allotment plots, and allotment sites, could be organized if climate resilience and water use efficiency were given higher priority. Natural England estimates 42% of people have mobility problems [34]. If allotments are to play a role in helping to promote public health and wellbeing, they need to be accessible to as wide a cross-section of the population as possible, but in 2019 only 28% of local authority allotment sites had any provision for plot holders with special needs or had a toilet [35]. We realized that organizing allotment plots and sites to be more water efficient provided an opportunity to address other important questions such as accessibility, indirect discrimination, sustainability and promotion of a sense of place and mental wellbeing. These have been combined into a design for an allotment of the future.

2. Methods

In this work, we discuss ways in which water can be used and saved more effectively. We explore the grouping of allotment plots and the use of shared water harvesting areas to increase the capacity for collection and storage of rainwater for irrigation and the use of permanent beds to facilitate water-efficient growing methods. A correlational approach combining qualitative and quantitative methodologies was used to design structures and site layout and take into account the social and emotional aspects of community gardening. The underlying principles used in our design were: high efficacy of plant growing (planting, growing and harvesting), increased resilience to climate change (in particular drought resilience), improved accessibility (this included reviewing Natural England and United Nations guidance on paths [34,36]), sustainability (use of environmentally friendly raw materials, United Nations sustainability goals [37] and caring for local wildlife) and affordability (dimensions of beds were matched to those of commonly available raw materials to minimize waste and simplify construction).

2.1. Methodology

To learn about current practices we visited more than thirty allotment sites and community gardens in the South West of England (the sites were selected opportunistically and included a mixture of urban, suburban and rural locations). We reviewed the websites of UK Allotment Groups and Community Gardens, together with digital stories collected by the Drought Risk and You (DRY) project (https://dryutility.info, accessed on 10 January 2021). The information collected was augmented by informal discussions with members of the National Allotment Society and the Somerset Smallholders Association.

On some allotment sites, plot holders have to rely on incident rainfall or water that they can carry from their homes. These growers need to use water efficient growing practices if they are going to adapt to changing climatic conditions. To better understand the water efficiency of different growing practices, we reviewed background publications

(peer-reviewed papers and grey literature) on plant water use and water management. We considered the ease with which different methods of improving water use efficiency could be actionable by amateur growers and describe those where there is good evidence supporting their efficacy. Survey data, provided by the National Allotment Society, about current water use on allotments were combined with estimates of potential future demand and used to calculate how much rainwater might need to be collected and stored to mitigate climate change.

We considered different systems to collect and store sufficient water to meet anticipated demand, to identify the most effective approach. To optimize the physical design of structures for rainwater collection and storage, we used the principles of Engineering Design [38] and methodology of the Theory of Inventive Problem Solving (TRIZ) [39]. A particular focus was placed on 'Human Centered Design' [40] as it was recognized growers would only voluntarily adopt new practices that offered tangible benefits.

To organize individual plots and plan the allotment site, so that plot holders could make the best use of available rainwater (whether incident or stored) we used these same principles [38–40], together with published guidelines for improved accessibility [34,36]. Throughout the design process, we were cognizant of sometimes conflicting requirements including affordability, sustainability, accessibility, ease of adoption and efficacy.

2.2. Prototyping

Due to the COVID-19 pandemic, we were unable to undertake any testing on allotments and instead carried out limited trials in our own gardens. Eight raised beds were built (to proposed dimensions) and a variety of plants (carrots, spring onions, onions, kale, courgettes, leeks, cabbages, cauliflower, broccoli and runner beans) grown, to test functionality and check for unforeseen issues (SB). Mulching and spacing, to reduce the need for watering were trialled with squashes and brassicas (SA). Drip irrigation and construction of raised planters were tested (NP). Methods of rainwater harvesting were used by all authors.

3. Improving Efficiency of Water Use

Water use efficiency is the amount of crop produced for the amount of water available (rainfall and irrigation) [41]. Summer rainfall in the UK is likely to decrease [28], and growers, particularly those in the east of the UK where annual rainfall can be less than that needed to meet potential evapotranspiration losses, may need to rely more on irrigation (watering). Watering can be time-consuming, hard work and expensive (if mains water or specialized equipment are needed). Plants only use a proportion of the water that is available. Commercial rain-fed crops use 15–30% of the rainwater available [42] while irrigated crops may use only 13–18% of the available water [42]. Even if water supplies are not limited, all growers should consider how to improve water use efficiency to reduce the work and time, and or cost, entailed in watering. Competing demands for water and increased demand for food have led commercial growers to make improvements in the efficiency with which water is used [43]. Amateur growers and allotment holders do not have to obtain maximum yields, or uniform crops, and may be able to use a range of strategies to make the most effective use of available water. A grower can aim for the maximum yield from a given area and water as required to achieve this, try to make the best use of available water, or try to reduce the need for water. Some of the most effective, and practical, ways of improving water use efficiency are to reduce the amount of water lost to the atmosphere and ensure that any applied water moves into the root zone [41]. Straightforward crop management practices to reduce the loss of water to the atmosphere include increased planting density, mulching and weed control. Applying water to the base of the plant through carefully directed watering, trickle or drip irrigation helps ensure water reaches the root zone.

3.1. Plant Density

In agricultural crops (barley (*Hordeum vulgare* L.), bean (*Phaseolus vulgare* L.), maize (*Zea mays* L.), and cowpea (*Vigna unguiculata* L.)), using more closely spaced rows reduced the amount of time that the soil surface was bare, reduced losses by evaporation and improved crop water use efficiency by up to 30% [41]. The reduction in evaporation was due to a combination of three factors. Firstly, the time that the soil surface was exposed to incident radiation was reduced. Secondly, humid air held within the plant canopy, increased the aerodynamic resistance to water vapour moment into the atmosphere. Thirdly, uptake of water by roots near the soil surface reduced the soil hydraulic conductivity and thus restricted the upward movement of water through the soil matrix [41]. Closer planting of many garden vegetables can produce a higher yield of plants that are more suited to domestic use [44]. Organizing the rows so that plants are staggered gives the maximum number of plants in a given area and ensures that the soil surface is covered; this will reduce losses of water by evaporation. Summer cabbages planted 35 cm apart, in all directions, produce heads about the size needed by most families, wider spacing (45 cm) gives larger heads but the smaller spacing gives 65% more plants in a given area [44]. Another way of keeping more of the soil covered is to use companion planting or intercropping [45,46]. Cropping systems, with several different crops grown together, particularly if the plants are very different in growth form, have demonstrated potential to improve water use efficiency and productivity particularly in small-scale vegetable production [47]. The 'three sisters' system of planting in which sweet corn, beans and squash are grown together is a good example of this [48]. The greater leaf cover increases the amount of light intercepted and reduces losses of water from the soil by direct evaporation. Growth of the individual species may be reduced and there may be an increased demand for water, above that which can be met by rainfall, but overall the productivity of the plot will be increased.

The opposite strategy is to space plants to make use of available soil water and reduce, or eliminate, the need for watering. The closer plants are growing the greater the competition between them for water, light and nutrients. If plants are widely spaced, the roots of each plant will have a larger volume of soil from which to extract water and nutrients; mulching the ground between the plants will reduce evaporation of water from the soil surface. There may be a lower yield on a per-area basis but, unless growing space is limited, the saving in terms of effort may be worth it. Many large vegetables can be grown like this. Various types of squash need water early in the growing season but once established can grow and produce a good crop with minimal watering. Brussels sprouts need little watering provided they are spaced about 1 metre apart [44]. The plants will be less dependent on applied water; reducing reliance on applied water is likely to become increasingly important in the future, when rainfall, during the summer, is predicted to be less than at present [28,30].

3.2. Mulching

Mulching helps to increase the efficiency of water use because it reduces the loss of water from the soil surface by evaporation while at the same time promoting the development of good soil structure, through the incorporation of organic matter. Soil water evaporation is reduced by about 5% for each 10% of the surface that is covered by mulch [49]. In commercial potato crops, in the UK, mulching reduced irrigation needs by 40 mm (from 131 mm) to 66 mm (from 258 mm), the equivalent of two irrigations, regardless of the agro-climatic region of the country [50,51]. The water savings were greatest in May and June, before the crop completely covered the soil, and were estimated to be similar for other root vegetable crops [50].

Regular addition of mulches and organic matter can increase the amount of available water held in the soil significantly. Across a wide range of different soil types, an increase in soil organic matter from 0.5% to 3% was associated with a doubling of soil available water capacity [52]. For example, on a silty clay loam soil with a soil water capacity of 120 mm (Appendix A), increasing the amount of organic matter could potentially increase

soil water capacity to 240 mm. Generating enough mulch to cover a whole plot is difficult. For example, four beds, 1.2 m by 1.8 m (total area 8.6 m^2), requires 12 × 70 L bags of mulch to get a 10 cm layer (840 L of mulch). However, if the site design includes communal composting areas (see Section 7) plot holders can arrange delivery of trailer loads of manure, mushroom compost or wood chippings and this can be a cost-effective way of obtaining mulching material [53]. Established beds require less new mulch year on year, down to 2.5 cm per annum.

3.3. Weed Control

Weeds growing amongst vegetables, or flowers, will compete for light, nutrients, space and water. Some common weeds transpire four times as much water as crop plants and, under conditions where water supplies are limited; weeds can reduce yields by 50% just through competition for water [54]. In sweet corn, weeds reduced soil moisture in the upper 46 cm of soil and were associated with a 96% reduction in yield, and the presence of black nightshade growing between tomatoes reduced water content in the upper 60 cm compared to non-weedy controls [54,55].

Although removing weeds will remove the competition for water it can leave areas of bare soil from which water will evaporate. If a crop has large leaves it may be more efficient, both in terms of effort and water use, to control weeds by weeding or hoeing when the crop plants are small; once the leaves are large enough to cover the soil and out-compete annual weeds, efforts can be directed against perennial weeds only. Alternatively, mulch can be used to suppress weeds, conserve moisture and improve the soil structure.

3.4. Directed Watering

When planting seeds, watering the drill, with about 1 L of water for every 1.3 m of row, before putting the seeds in, ensures that the seeds are planted in the optimum conditions for germination [44]. Watering after planting may cause a 'cap' to form on the surface of the soil that can prevent the seedlings from emerging. Once seedlings have germinated, watering should aim to encourage the development of strong deep roots, the best way to do this is to water close to the base of the plant. Transplanted vegetable plants need regular watering, about 150 mL water directed onto and around the base of the plant every day, until the plant has recovered from transplantation shock [44]. After plants have established water should be applied near the roots, so that losses by evaporation from the soil surface are reduced. It is more effective to apply larger volumes of water occasionally, so that the water penetrates into the soil; work at the National Vegetable Research Station (NVRS) [44] suggested using at least 11 L m^{-2}. Applying little water frequently encourages roots to develop at the surface where they can quickly dry out. When the temperature increases from 10 °C to 20 °C the rate of evapotranspiration doubles, from 1–3 mm day^{-1} to 4–7 mm day^{-1} [49]. Watering early in the day, when the ground is cool, or late, after the sun has set, reduces the amount of water lost by evaporation from the soil and allows more of the water to penetrate the soil [49,56].

Trickle irrigation and drip irrigation are automated or semi-automated systems that can be set up to ensure that water is directed slowly and evenly to the roots of the plant. Water losses by direct evaporation from both the soil surface and plants leaves are minimized because the pipes containing the water can be placed close to the plant, or covered by a mulch. In commercial vegetable production, the irrigation efficiency of trickle (or drip) irrigation can be 80–90% compared with only 50% for sprinklers [43]. Irrigation efficiency (IE) is the ratio of the amount of water consumed by the crop to the amount of water supplied through irrigation (surface, sprinkler or drip irrigation) [57]. Trickle irrigation permits growers to irrigate a larger area (up to 40% larger), for the same volume of water, than conventional methods of application [58]. Trickle irrigation usually entails supplying water from a container, via a small diameter pipe attached to a series of nozzles; water can be supplied using gravity or using a small pump that could be powered by a solar panel. If low-pressure (gravity) feed is used, ideally, the pipe will be 10 mm in diameter, to reduce

blockages. It takes some time to set up a trickle irrigation system and the cost, to buy and replace the pipes, can be high; so it is best used for high-value crops. For amateur growers, on an allotment, a simpler arrangement is to use a perforated pipe (seep pipe), and lengths of old garden hosepipe that have developed leaks can be reused in this way [31].

Drip watering systems use gravity to feed water from elevated containers (e.g., a plastic bottle or bag of 2–5 L capacity) to plants via plastic tubing. A manual valve regulates the flow rate. This is particularly good for growbag watering, is inexpensive and can easily be set up in a glasshouse or polytunnel (Figure 2). The flexible setup can be re-arranged to accommodate different plants and layouts. Nutrients can be added to the water but care must be taken not to overwater, as this will wash nutrients out of the soil. Linking the water container to the pipework via a battery-powered valve allows the plants to be automatically watered before sunrise. This minimizes evaporation losses.

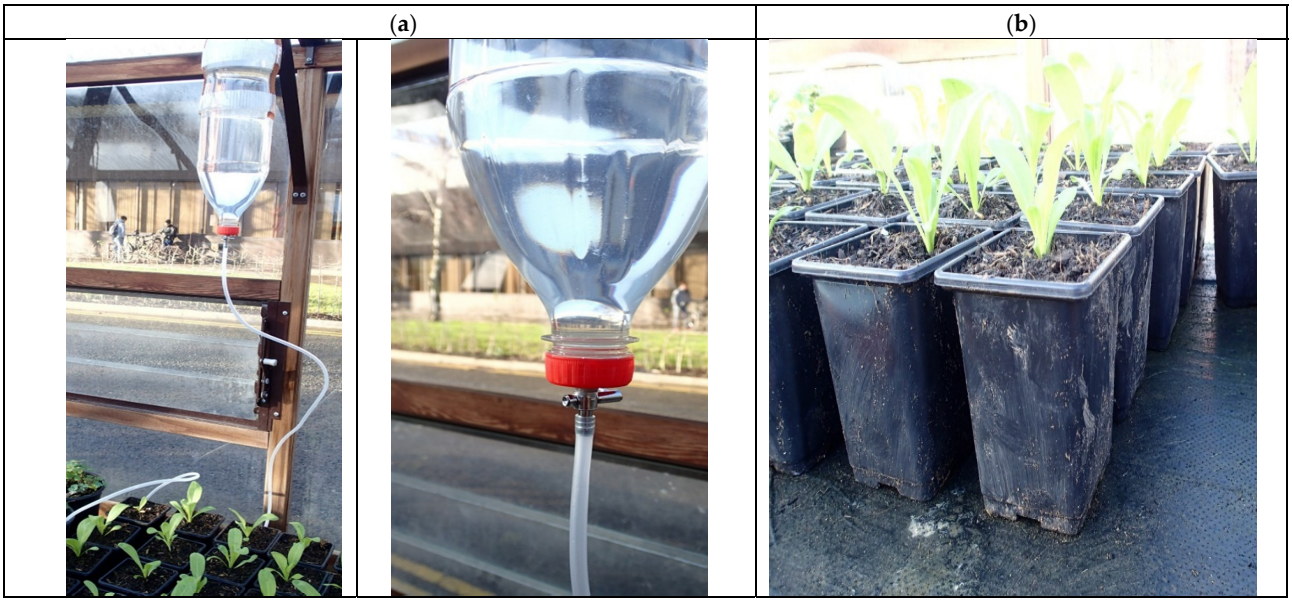


Figure 2. The use of drip irrigation and capillary matting in a greenhouse allows water to be supplied efficiently. (**a**) Drip irrigation used to water pots in a glasshouse. (**b**) Pots of seedlings standing on capillary matting.

Pots and trays of small seedlings can dry out very quickly, especially in windy and sunny weather. In commercial horticulture, capillary watering systems are widely used in the production of seedlings of ornamental and vegetable plants, and for growing soft fruit [58]. This system is very easy to set up. Pots are placed on capillary matting, often in large trays (Figure 2). The matting absorbs and holds water that can be drawn up from water held in a nearby container. A shallow gravel-filled tray can be used in place of capillary matting, to minimize the use of plastics.

3.5. Watering Requirements

Different types of plants have different watering requirements. Some plants need watering throughout the growing season but others have growth stages that are sensitive to water shortage (Appendix D gives the water requirements, in the UK, of some vegetables). Grouping plants by water needs can help the grower to use his, or her, time and water supplies most efficiently and most effectively. Leafy crops like spinach, lettuce, rocket, and plants sensitive to water stress, such as tomatoes, can be grouped close to the water supply and crops that will grow with little added water such as sprouts and leeks could be further away [44]. Different crops respond differently to watering. Many crops, particularly those that produce fruits or seeds, such as maize, beans and tomato, have a moisture-sensitive growth stage [59]. Some of these can achieve almost as high a yield with sub-optimal,

compared to optimal, watering. In maize 70% of the maximum yield can be obtained by replacing 45% of the water lost through evapotranspiration, but tomatoes are more moisture sensitive and need 90% of evapotranspiration to be replaced to give 70% of the optimum yield (Figure 3) [59]. An allotment gardener with limited time or limited amounts of water might prefer to put the effort involved into watering tomatoes than into maize.

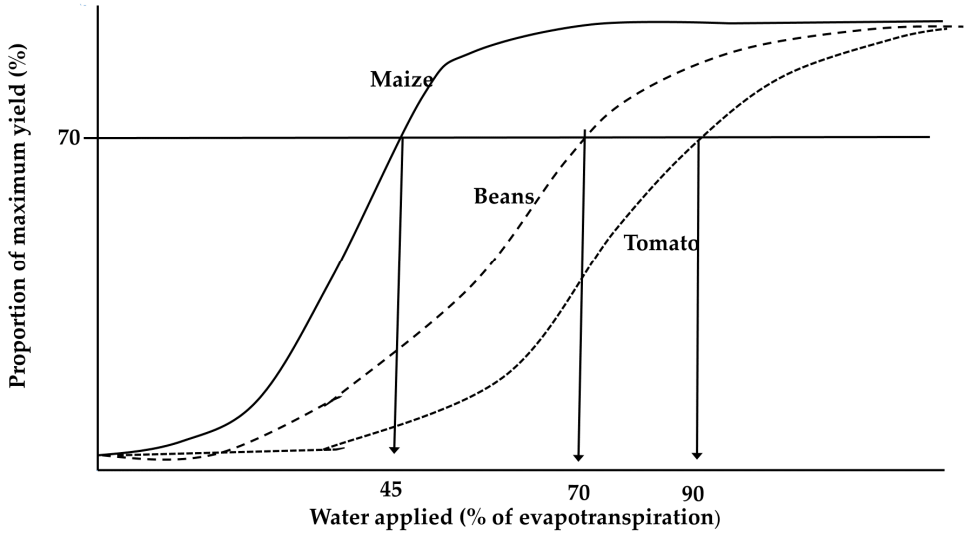


Figure 3. Response of maize, beans and tomato to watering (Adapted from De Pascale et al. (2006) [59].

Cabbages need a consistent water supply to obtain maximum yields [44], however acceptable yields can be obtained with less water. Two waterings were sufficient to obtain 80% of the yield obtained with eleven waterings, and one watering two weeks before cutting still gave 65% of the maximum yield [44].

Once plants have enough water, to meet their growth requirements, adding more water will not increase the amount of useable crop and may even be detrimental. Overwatering of head-forming vegetables such as cabbage or cabbage type lettuce (e.g., 'Iceberg' or 'Webb's Wonderful') can cause the heads to split [44]. Gardeners with limited time and or access to water can focus on high-value crops. New potatoes (rather than main-crop potatoes) are harvested early in the summer before the soil becomes dry (over the summer) and are usually expensive to buy [60,61].

3.6. Avoid Water Shortages

In arid and semi-arid regions of the World, growers have learnt to plan the planting of crops to coincide with times when rainfall is able to provide the crops water needs. In South West Australia, faba beans (*Vicia faba* L.), commonly known as broad beans in the UK, produced a much higher yield when sown early in the season so that they were able to take advantage of autumn and winter rainfall [62]. Water use efficiency of the crop is improved because as rain falls the crop takes it up, and as the crop develops, through the winter wet season, it gradually covers the soil so that water losses by direct evaporation from the soil surface, in the spring when temperatures are higher, are reduced.

In the UK, plants, such as broad beans, spring cabbage or chicory, sown during the autumn develop their root system during the winter. These autumn-sown plants and perennial plants, such as asparagus and Babington leeks, or perennial varieties of crops usually grown as annuals, such as Swiss chard and kale, will be able to make optimum use of available water because they will be growing and using water at the time of year when rainfall exceeds water use. Growing these vegetables is a good way of avoiding the need to water and adapting to the predicted reduction in summer rainfall in the UK. The period 2009–2018 has seen 15% fewer days of air or ground frost, and 15% more growing degree-days, compared with 1961–1990 [63], and these trends are predicted to continue [28].

A growing degree-day is when the temperature is above 5.5 °C [63]. These changes will extend the growing season and allow a wider range of crops to be grown during the winter.

3.7. Grow Drought Tolerant Plants

Many herbs, such as oregano, thyme, sage and rosemary, are naturally drought tolerant and once established should not need watering. Some varieties of vegetable are more drought resistant than other varieties. Many seed catalogues provide information about which varieties are more tolerant of water shortages, and file S1 gives some sources of advice. Cos lettuce requires less water than cabbage lettuce (such as 'Iceberg' or 'Webb's Wonderful') and some varieties of potato, such as 'Desiree', 'Marfona' and 'Robinta', are considered drought tolerant [64].

4. How Much Water Is Needed on an Allotment?

Watering is important to all gardeners, but it is difficult to find information about the amount of water used by individual plot holders. In 2019, the National Allotment Society conducted a survey of water use on allotments [65]. This survey found that estimates of annual water use ranged from 0.48 to 176 L m^{-2} with an average of 21 L m^{-2}. At one site, in the North West of England [65], between 2011 and 2019 annual water use per plot was just under 8000 L (~8 L m^{-2}). Another allotment holder reported that on his site, mains water use currently varies from 1800 to 15,000 L per plot per annum (1.8 to 15 L m^{-2}), on average, 6 $\pm$ 3 m^3 per plot per year [65]. At an allotment site in the West Midlands plot holders used on average 330 L m^{-2} each year (66 m^3 per plot) [66]. Water on allotments is used for a number of different purposes including watering plants, watering seedlings, cleaning pots, seed trays and tools, for livestock or wildlife and washing hands. Although the amounts of water needed by an individual plot holder depend on many factors, including local climate, soil type and type of plants grown (using the information in Appendix A and File S2), we can make some rough estimates of how much water might be needed (Table 2). Water efficient growing practices (Section 3) can reduce the amount of water that might need to be supplied, but in drier parts of the UK or on sandy soils (http://www.landis.org.uk/soilscapes/index.cfm, accessed on 4 February 2021), if mains water is not available, rainwater falling in the winter will need to be stored to supply demand during the summer.

Table 2. Estimation of the amount of water needed annually on an allotment.

Type of Water	Used for	Amount (Litres)	Comments
Rainwater	Watering plants	Up to 19,000	See Appendix A for assumptions and calculation, up to 200 L per day per plot during the summer months
	Cleaning	250	45 L twice each year, for washing pots and seed trays, 45–60 L cleaning a glasshouse and staging. Weekly 2 L to clean hand tools.
	Total	19,250	
Mains water	Watering glasshouse seeds and seedlings	200	Short-term demand, about one month. Mains water recommended to prevent disease [31]
	Livestock	6000	Based on a flock of twelve hens, values for other livestock in File S2
	Handwashing	520	Flowrate for a hand basin tap is approximately 10 L min^{-1}. The water flow for 30 seconds is 5 L, i.e., 5 L of water per hand wash. Assuming 5 L per visit, with two visits per week.
	Total	6720	

5. Rainwater Storage and Collection

If mains water is available it can be a significant cost for the plot holders. On two allotment sites in Oxford, water charges are 42% of the allotment association's annual budget [67]. Rainwater is free and considered by the Royal Horticultural Society (RHS [68]) and many growers, to be better for plants. Collecting and storing rainwater should be a central concern when planning any new allotment site or garden, and when redeveloping an existing site.

On most allotment sites, rainwater collection is at the discretion of the individual plot holder. Rainwater can be harvested from artificial structures (such as roofs of sheds, greenhouses or polytunnels) or from the landscape (swales, terraces or French drains, runoff from paths and other areas). Storage is much easier if water is collected above ground level so that gravity feed can be used to move water to and from the container; however, on some sites, this may not be possible because local rules prevent plot holders from erecting permanent structures. Gardeners have found many inventive ways to collect and store water [69], but there is a limit to the amount of water that an individual can collect and store. It is more efficient to collect and store water on a larger scale; either as a centralized site water facility, or using a semi-distributed system where neighbouring plot holders share water.

Our analysis (Table 3) indicated that for most allotment sites, a semi-distributed rainwater collection and storage system would be the most practical because it would increase the amount of water that could be stored and minimize the distance between the source of water and the site of use. At the same time, it would encourage neighbours to cooperate, and this would promote plot holders to develop a sense of place, responsibility and ownership. Although nothing would prevent one individual from using more water than another, these individuals would be easily identifiable because the number of plot holders sharing each water source is small. All plot holders will be close to a source of water so that people who cannot easily carry watering cans will not be disadvantaged.

Table 3. SWOT analysis of types of rainwater collection/storage/distribution systems.

	Individual	Semi-Distributed	Centralized
Strengths	Low cost, funded directly by plot holder		
	Low complexity, easy to implement & maintain		
	Independent control by plot holder	Opportunity for plot holders to customize	
		Promotes cooperation between adjoining plot holders	Promotes cooperation across site
		Large storage capacity	Very large storage capacity
		Awareness of stored water level possible	Monitoring/awareness of site's stored water level
Weaknesses		Medium cost, funded by site and/or plot holders	High cost, funded by site
		Medium complexity, some expertise required	High complexity, specialist knowledge required
		Needs cooperation to set up	Site wide agreement to set up

Table 3. *Cont.*

	Individual	Semi-Distributed	Centralized
			Lack of individual responsibility
	Water storage capacity usually less than desirable		
	People with limited mobility may not be able set up a system		
	Can make site look untidy		
Opportunities	Individual creativity	Develop sense of responsibility towards neighbours	
		Can be incorporated into other structures (e.g., local shelter & tool storage)	Can be incorporated into other structure (e.g., site hut for communal use)
		Drip irrigation easier to implement due to pressure	Drip irrigation easier to implement due to pressure
		Semi-distributed hubs can be interconnected	
Threats	Lack of maintenance		Who is responsible for repair if it breaks
			Site vulnerability to vandals/accident

5.1. How Much Water Can Be Collected?

A shed or greenhouse of 2 m × 3 m would be able to collect 3.84 m^3 (3840 L), assuming 800 mm annual rainfall (Appendix B). To use as much collected rainwater as possible requires significant water storage capacity. Normally about 80% of collected water is used, as some will be lost in storage due to evaporation. A high level of water resilience is desirable because plant growth is reduced by even a short period without adequate water. We used our estimates of water demand and data from the NALGS survey (Section 4 [65]) to provide *typical* values of water demand and collection. These generated a prototype design that was adjusted to accommodate real-world factors such as discretization (due to water storage capacity in demarcated volumes). After several design iterations, two designs (Figure 4, Table 4 and Appendix C), were shortlisted for further consideration. The modular design allows the area of rainwater collection and storage capacity to be fine-tuned to local site conditions.

5.2. What Is the Optimum Structure for Rainwater Collection and Storage?

An array of intermediate bulk containers (IBCs) or plastic barrels is often the most practical, and economical, storage option. Figure 4 shows a stylized representation of a group of four allotment plots with a shared rainwater storage area. Grouping four plots together provides a degree of 'averaging' in consumption (e.g., different crops on each plot). Grouping has the secondary benefit of increasing the mechanical rigidity of the structure, this may be important on exposed sites. The design assumes some maintenance to mitigate peak roof loading (e.g., periodic partial roof clearing of snow build-up). This arrangement would allow approximately 8000 L of water to be stored per plot, sufficient to supply 200 L per plot per day for around 40 days. If 240 mm of rain fell during the summer (Appendix A), based on our design, 3072 L of water could be collected during

the summer, sufficient for an additional 15 days. If water-efficient growing practices were used (Section 3), or in cooler and wetter regions of the country less water might be needed but if changes in temperature and rainfall patterns were more extreme than currently predicted [26,29,30] more water might be needed.

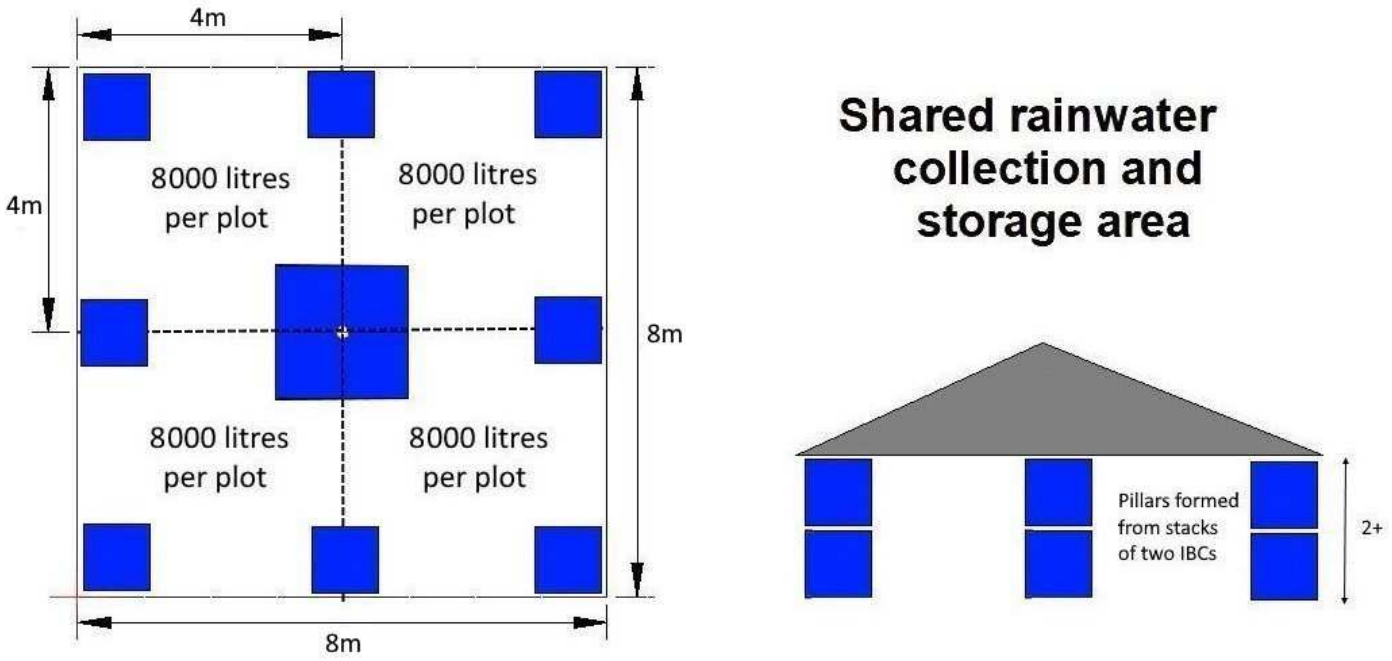


Figure 4. A stylized representation of a group of four allotment plots with a shared rainwater storage area.

The Theory of Inventive Problem Solving (TRIZ) methodology [39] was utilized to optimize the design of the structure for rainwater collection, storage and utility area for plot holders (Table 4). A dual pitched design, providing 16 m^2 of rainfall collection area, gave the best balance between ease of construction and efficient use of materials. The design and dimensions of the structure can be altered to match the budget and building materials available. For example, the roof could be made from second-hand scaffold poles (Appendix C) and the number of IBCs reduced or increased. During winter months or times of high summer rainfall, the rate of water collection will surpass consumption and may exceed storage capacity. The excess water needs to be removed, so that adjoining plots are not waterlogged. French drains (File S3), or a drainage pipe, could be used to direct excess water to a local soakaway(s) or to a swale or pond, which can form a wildlife feature to encourage pollinators and other beneficial wildlife.

Table 4. Evaluation of three possible roof designs for water collection.

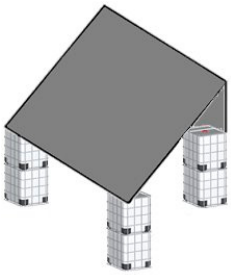
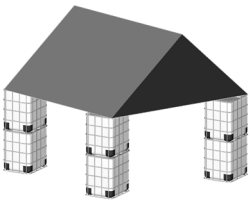
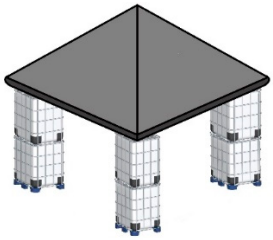
	Mono Pitched (Shed Roof)	**Dual Pitched (Triangular Prism)**	**Quad Pitched (Square Pyramid)**
Appearance (only three corner pillars shown for clarity)			

Table 4. *Cont.*

	Mono Pitched (Shed Roof)	Dual Pitched (Triangular Prism)	Quad Pitched (Square Pyramid)
Total rain collection area	64 m^2	64 m^2	64 m^2
Rain collection area per plot	16 m^2	16 m^2	16 m^2
Roof material with 5° pitch	~70 m^2	~64.3 m^2	~64.3 m^2 + waste
Ridge height with 5° pitch	~3.1 m	~2.7 m	~2.7 m
Roof material with 20° pitch	~91.4 m^2	~68.1 m^2	~68.1 m^2 +waste
Ridge height with 20° pitch	~5.3 m	~3.8 m	~3.8 m
Ridges	0	1	4
Total length of guttering	8 m	16 m	32 m
Build complexity	Medium	Medium	High
Wind aerodynamics	Poor	Average	Good

The body of the structure is formed from rigid Intermediate Bulk Container (IBCs) each with a storage capacity of 1000 L and external dimensions of 1000 mm (width), 1200 mm (depth) and 1170 mm (height). The IBCs are double stacked to form pillars in the (four) external corners, in the sides and (four) in the middle.
Corrugated sheets of steel (galvanized) and plastic/composite are a cost effective, rigid, roofing material. Alternatively, sheets of wood (e.g., treated plywood or OSB) with appropriate beams could be used. Corrugated sheets allow the roof pitch (e.g., 5°) to be lower than with traditional roofing materials such as tiles & shingles. A 20° pitch provides better debris clearing (including snow) and sounder waterproofness than a flatter pitch.
Three roof designs were considered. All three roof types have their own merits. However, on balance it was considered that 'dual pitched' offered the best overall solution for this application. In particular, 'dual pitched' benefits from efficient use of raw materials and ease of connecting gutters to IBCs.
A wide range of structural enhancements are possible to suit the plot holders' requirements. By way of example:

- Transparent sheets could be incorporated into roof to allow plants to be grown under cover
- Photovoltaic (PV) panel(s) or bio-reactors [70] could be located on the roof to provide electrical power for application such as drip irrigation pump or LED lighting
- The undercover area could be partitioned with sheets (e.g., wood) to form storage rooms for tools or crops
- Seating could be added to take advantage of shade during hot weather
- Water use can be monitored by fitting a meter to the outflow. If necessary, additional IBCs can be added.

6. Cultivation and within Plot Layout

Within plot cultivation and layout needs to protect and improve soil structure. Soils are a mixture of mineral material, organic matter, soil air and soil water. The percentages of different types of mineral material, particles of clay (<2 µm diameter), silt (2–50 µm diameter) and sand (50 µm–2 mm diameter), determine the soil texture [71]; for example, a sandy clay contains >35% clay, <20% silt and >45% sand. Soil structure, the way in which the solid particles (sand, clay, silt, stones and organic matter) and spaces (pores) between them are organized, is the architecture of the soil [72]. Soil texture and soil structure together influence the amount of water held within the soil (soil water/moisture capacity). Sandy soils with a coarse texture store less soil water than finer-grained clay soils [73], although not all of the water held in the soil will be available to plants.

The spaces, or pores, within a soil are as important as the mineral particles. The spaces in the soil contain a mixture of water and air, water held in the soil spaces contains dissolved nutrients and the larger spaces (macropores) allow roots and soil fauna to penetrate the soil [71,73,74]. After rainfall, or watering, all the spaces within the soil may be filled with water, and the soil is said to be saturated [73]. Water will drain under the influence of gravity, from the largest spaces (macropores) and be replaced by air (Figure 5), and the soil

is then said to be at field capacity [73]. Some water is bound very tightly, adsorped, onto the surface of soil particles or held in micropores and this is not available to plants [71]. Water held in the mesopores, sometimes called capillary water, is the reservoir of water available to plants [71,73]. If plants have taken up all water held in the mesopores, the plants will wilt; this is the wilting point. The amount of water held within a soil between field capacity and the wilting point is the plant available water. Good soil structure is essential for plant growth because it influences drainage, soil moisture content and the amount of plant available water, mineralisation of nutrients and rates of root extension [71–74]. The UK has a very wide range of soil types (http://www.landis.org.uk/soilscapes/index.cfm, accessed on 2 March 2021) [75], reflecting the different geological and climatic regions of the country [75]. Each soil type has its own structure and water holding capacity [73,75].

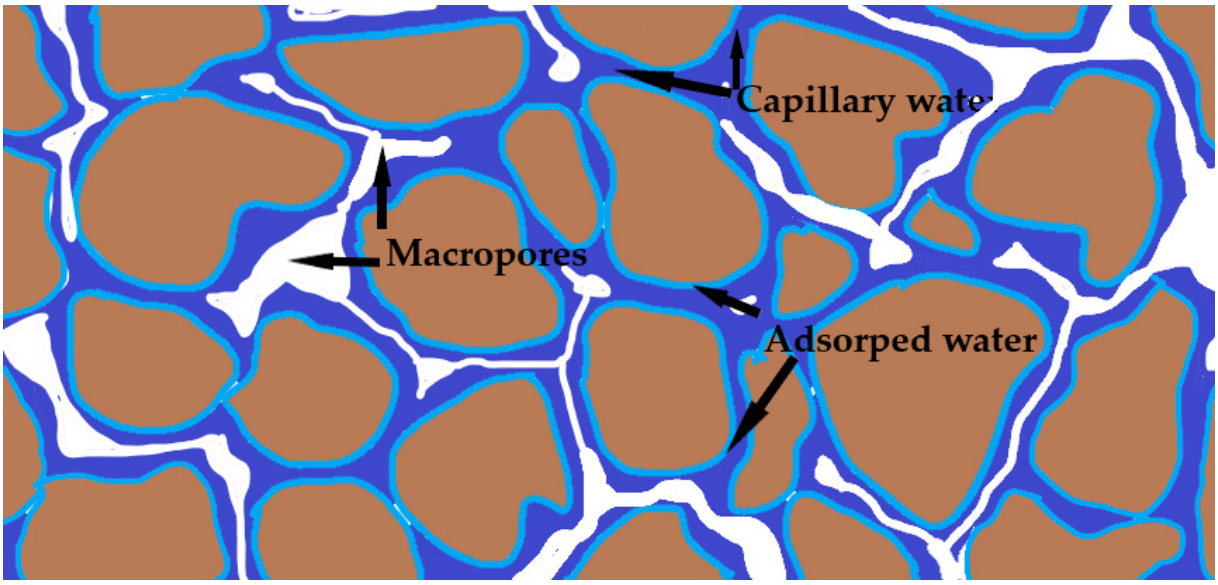


Figure 5. Diagrammatic representation of a soil at field capacity, showing macropores (>75 μm diameter) containing water and air, mesopores (75–30 μm diameter) containing water held by capillary forces, and micropores (<30 μm diameter) and particle surfaces where water is tightly bound (adsorped) and not available to plants. Based on [71,73].

Soil structure can be damaged by cultivating when the soil is too wet or by repeated trampling. In the UK, the structure of soils developed over silts, clays and shales (http://www.landis.org.uk/soilscapes/index.cfm, accessed on 2 March 2021) [75] is particularly sensitive to damage [71]. If the soil structure is damaged the soil can become compacted. In an ideal soil, there will be roughly 50% solids and 50% spaces, [74], and the spaces will contain equal amounts of air and water; in contrast in a compacted soil, solids may be around 70%. Compacted soil has fewer and smaller pores, therefore the capacity to hold water and air is reduced, and water cannot infiltrate into the soil as easily as in non-compacted soil [71,73]. This makes compacted soil more susceptible to erosion and capping [76,77]. Compacted soil can become anaerobic [77,78], this will affect the availability of mineral nutrients and the growth of plant roots, soil fauna and soil microorganisms [71]. Although climate change is predicted to reduce summer rainfall, the intensity of rainfall events in both summer and winter is likely to increase [28,30]; on compacted soil, the increased erosive power (erosivity) of the rain is likely to increase erosion. When the soil is compacted plant growth is inhibited. The lack of spaces within a compacted soil prevents roots from penetrating into the soil and thus reduces the volume of soil from which the plant can absorb water and this, combined with the reduced amount of water held within the soil, reduces the amount of water available for plant growth. The yield of vegetables can be severely reduced in compacted soil (Table 5 [78]). In Maris Piper potatoes, soil compaction reduced yields by between 18% (for unirrigated potatoes) and 39% (for

irrigated potatoes) [79]. The greater effect of compaction on irrigated potatoes reflects the fact that water is not easily taken into compacted soil and will be lost through run-off and evaporation and thus not be available to the plant.

Table 5. Reduction in yield of some common vegetable crops by compaction. Data taken from Grassbaugh and Bennett 1998 [78].

Crop	Compacted Yield/Uncompacted Yield (%)
Snap bean	25
Cucumber	34
Cabbage	34
Squash	30
Sweet Corn	45
Tomato	44

Soil structure can be improved by incorporating organic matter, either by adding material such as farmyard manure or mushroom compost or through green manuring [52,80]. On agricultural soils application of organic materials (biosolids, composts, livestock manures) is widely recommended, and practiced, to increase soil organic matter levels and thus soil structure, microbiology and nutrient levels [80]. Green manures are fast-growing plants, often legumes such as alfalfa (*Medicago sativa*) or crimson clover (*Trifolium incarnatum*), sown to cover bare soil and grow over the winter months. They can be turned into the soil (before flowering) to increase the organic matter content of the soil, which, by improving soil structure, increases the water holding capacity. In temperate zone soils, such as in the UK, organic matter provides a substrate for the growth of microorganisms within the soil. These microorganisms produce a range of polysaccharides and proteins that act as a glue, which binds soil mineral particles into aggregates, and thus help to develop and maintain soil structure [73]. Maintaining a vegetative cover on the soil during the winter also helps to protect the soil surface from the erosive power of rainfall and thus reduces soil erosion and capping during periods of heavy rainfall. The incorporation of symbiotically fixed nitrogen into the soil, thereby helping to maintain soil fertility is another important benefit [81].

6.1. Paths and Beds

The traditional layout of allotment plots, in long rows or large blocks (Figure 1), and some traditional gardening practices, such as double digging [15], can make promoting soil structure and implementing water efficient practices difficult. In recent years the 'no dig' approach [82,83] has become popular, and if followed is very successful in controlling weeds and pests while at the same time improving soil structure. Central to the success of the 'no dig' approach is the setting up of permanent beds surrounded by paths. The paths need to be wide enough to allow space for kneeling while weeding or moving wheelbarrows (Figure 6). It is important to make sure that beds are not too wide or it will be difficult to reach the centre for harvesting (Figure 6). Even if 'no dig' is not followed it is a good idea to set up permanent beds so that most traffic, and associated soil compaction, is confined to specific areas and the soil structure on the growing areas improves. Figure 6 shows a stylized representation of four adjoining allotment plots, sharing a common water storage system. Having more paths will reduce the area available for cropping; however, studies of allotments have shown that it is unusual for all the available area to be used for crops. On allotments in Leicester, on average cultivation of fruit and vegetables used only 51% of the available area, with hard surfacing, permanent structures, compost heaps, fruit trees and flowers bringing the used area up to 67–70% leaving around 30% of the available ground uncultivated [8]. Thus losing a few per cent of the available area to wider

and better paths would have a negligible effect on the area used and in fact, by improving accessibility, might actually increase the amount of ground under cultivation. Dividing the plot into smaller beds makes it easier to implement water-efficient growing practices because plants with a similar water requirement can be grouped together. Plants growing close together or needing frequent watering could be planted close to the water supply, and for an amateur grower, trickle irrigation is easier to set up in a limited area. Crops that are widely spaced, using rainfall and stored soil water, perhaps combined with mulching could be sited further away from the water source. Weeding and mulching a smaller bed can be done without trampling and compacting the adjacent soil.

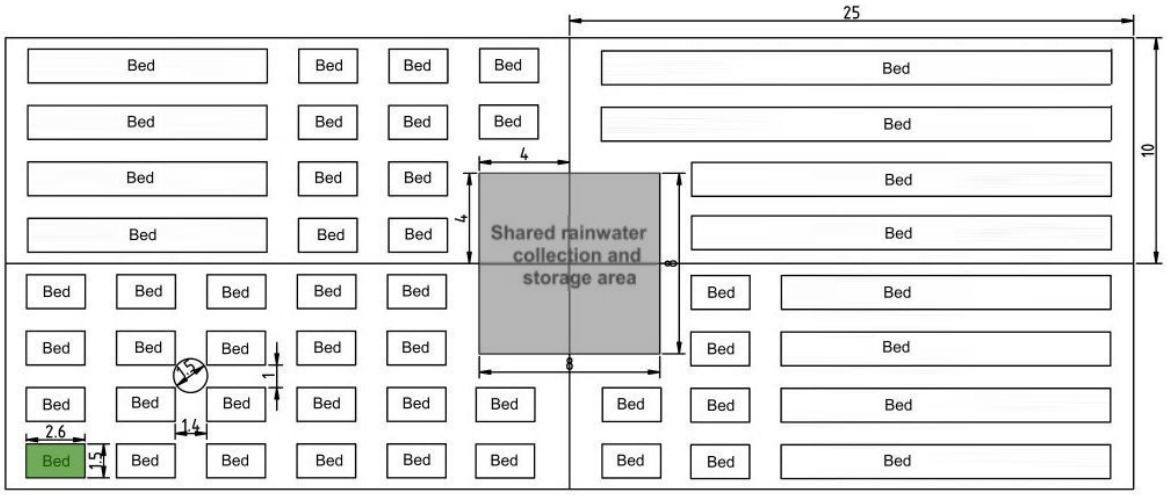


Figure 6. A stylized representation of four adjoining allotment plots, sharing a common water storage system. For simplicity, the beds are shown as rectangles. One plot is subdivided into 22 small beds 2.6 m × 1.5 m, separated by paths 1 m wide, allowing a 1.5 m turning circle at the intersections. A width of 1.5 m was chosen based on discussions with gardeners of different ages and a wheelchair user, 2.6 m is a widely available length of timber in the UK and thus an economical size to use. The size of the bed can be adjusted to suit individual needs or available materials. Paths will use approximately 40% of the available area, only a little more than that taken up by paths and uncultivated ground in the study of Leicester allotments [8]; if longer beds are used even less area is taken up by paths. The diagram shows how the plot layout be modified to suit different crops or to allow siting of a greenhouse or polytunnel.

6.2. Greenhouse and Polytunnel

Greenhouses and polytunnels allow growers to start plants early and to grow crops that, in the UK, do not always crop reliably in the open. Plants in a greenhouse will need watering. It is often possible to collect water from the roof, but a single water butt may not hold sufficient water to meet demand and water will need to be carried from elsewhere. Siting of the greenhouse in relation to water supplies and paths can help minimize compaction caused by carrying water. Collecting rainwater from polytunnels can be challenging. Installing timber rails (e.g., 38 × 63 mm), approx. 1 m off the ground, on the inside of the polytunnel, allows square section guttering to be screwed onto the outside. To ensure rainwater runs directly into the gutter, silicon sealant can be applied between the gutter and polythene sheet.

7. Site Layout

Careful site layout provides the opportunity to make an allotment site more resilient to future climate change and to improve accessibility and promote the development of sense of place. There are many possible elements within the site design and layout; we consider well laid out paths, a pond or wildlife area, different sizes of plot, a communal building, toilet, mains water supply, and composting areas among the most desirable.

7.1. Paths

Few allotment sites are completely flat or uniformly well-drained. In agricultural systems, contour ploughing can reduce erosion, and control runoff. Ploughing along the contours creates a series of small ridges that hold back water, stopping it from running downslope and encouraging water to soak into the soil. Natural England recommends contour ploughing as a cost-neutral way of improving crop productivity, soil structure, and reducing loss of topsoil via erosion [84]. The improvement in rain infiltration into the soil can be very significant; Whitescarver (2016) cites an example from the USA in which 280 mm of rain fell, a field cultivated along the contour took up 170 mm compared with 53 mm in a non-contour cultivated field [85].

Regularly used paths inevitably become compacted, and this will prevent water from infiltrating into the soil easily. Ideally, permanent paths should follow the contours of the site, and if practical, be made of a permeable material [86]. This will reduce runoff during periods of intense rainfall (rainfall intensity is predicted to increase in the near future [28]) and encourage infiltration into the soil since the compacted area of soil under the path will act as a barrier to through-flow in the surface layers of the soil. Paths should be wide enough for a wheelbarrow, wheelchair or pram to encourage a range of different potential users The United Nations Enable guidance recommends a minimum path width of 0.9 m and a maximum slope of 1:20, laying out paths along the contours makes it easier to avoid steeply sloping paths [36].

7.2. Pond and Wildlife Area

An area that is lower and tends to be wetter than other parts of the site, is the ideal place to create a wildlife area with either a small pond or bog garden. Excess water from rainwater harvesting systems (Section 5) during periods of high rainfall can be directed to this area, to prevent this water causing problems by waterlogging adjoining plots. In urban areas, allotment sites can act as a valuable haven for wildlife. Biodiversity (the variety of different plants and animals) on allotments can be promoted without compromising the role of the allotment garden to produce fruit and vegetables. An area dedicated to wildlife will help to encourage pollinators and animals such as hedgehogs, frogs and toads that eat many of the invertebrates that are considered pests on allotments such as slugs and snails [87,88].

7.3. Different Sized Plots

Not all allotment gardeners will need, or want, a full-sized plot. The site should have some areas with smaller plots. People with mobility problems, whether due to illness, age or young children, may not be able to tend a conventional plot easily. Natural England estimates that 42% of the population have mobility problems [34]. These people may prefer to have raised beds or planters; ideally located on a path that is level, or on a gentle gradient, and suitable for use by wheelchair users or people with prams, and preferably close to the site entrance so that users can drive to the site if needed.

7.4. Communal Building

On allotment sites that have a communal building, this communal space is often multifunctional; acting as a tool store, water collection point, a place to swap crops/seeds, a meeting area, and on some sites as a focus for social activities. On one site, at Minnowburn, the plot holders have added an oven, to cook pizzas during communal activities [89]. In 2019, a survey of local authority owned allotments sites found that only 30% had a communal building [35]. For safety, any petrol power tools (such a shared lawnmower) need to be stored in a separate building. The building needs to be positioned somewhere that is easily accessible for everyone.

7.5. Toilet

Lack of a toilet discourages people from spending long periods of time at the site, and is a form of indirect discrimination. In 2019, only 28% of local authority allotments sites had a toilet [35] even though access to sanitation is one of the United Nations Sustainability goals [90]. The toilet should be located close to the entrance and communal building, as this will make the site more attractive, particularly to people with families. A rota for maintenance and costs could be included in the site rent.

Compost toilets are ideal for allotments (Figure 7) [91], as they do not require a connection to a septic tank or sewer system. A compost toilet is a type of dry toilet that that does not use water or chemicals to take away the waste. Instead, waste is decomposed, under aerobic conditions, by microorganisms (mainly bacteria and fungi); this process usually takes several months. However, their output usually requires a second composting stage to reduce pathogens further. The fertilizer produced from these toilets can be used around fruit bushes and trees but should not be placed directly onto vegetable growing plots. As excrement can contain potentially harmful pathogens hand washing and drying facilities should be provided [92], ideally mains water. If the site cannot have mains water, anti-bacterial gel should be supplied [93].



Figure 7. Photograph of composting toilets at University of Bristol Botanic Gardens and diagram showing how the system works. Diagram courtesy WooWoo [91].

7.6. Mains Water Supply

Where practical there should be at least one mains water tap per site to supply water for watering seedlings (Section 4), washing hands, cleaning injuries, drinking and livestock (Section 4). If the site contains a shared communal building (potentially with an adjoining toilet), it makes sense to locate the single mains water tap there. A self-closing tap will minimize mains water consumption.

7.7. Communal Composting Areas

Just as scale offers benefits in terms of efficiency of water collection/storage (Section 5), so does site delivery of bulk materials including; woody waste, grass cuttings, manure and used pallets. Ideally, there should be a central area, accessible via a permanent track, where bulky material can be delivered. Depending on the composition of deliveries: shredded woody material can be used for mulching and partly decomposed organic material turned into compost to improve soil structure and thus soil water availability (Section 6). Processing bays (for decomposition) can easily be formed from pallets. Composting in larger heaps raises the internal temperature, which speeds up natural breakdown. Collaborating

on processing and sharing the outputs helps to create a team spirit, foster cohesion and encourage additional joint (rather than individual) activities on the site.

8. The Allotment of the Future

The nexus of water used for plant growth on an allotment is complex (Figure 8). Plant growth on an allotment is a combination of natural growth, using soil water and incident rainfall, without human intervention (Region (a)) and growth with increased water availability due to human intervention (watering) (Region (b)) (Figure 8). Water collection rate is linked to the rainwater collection area. Storage capacity is linked to the capacity to hold rainwater over a prolonged period with minimal loss (Section 5). These parameters can be increased at a higher cost; a balance between the two parameters usually provides the most cost-effective solution. The consumption rate can be partly reduced by more efficient water use (Section 3). The environment affects all the parameters. Storage capacity is mostly independent of time, but water collection and consumption rates vary throughout the year. Collection rate is determined by precipitation. The consumption rate is increased by elevated temperatures. Temperature and humidity both affect the rate of evaporation of stored water.

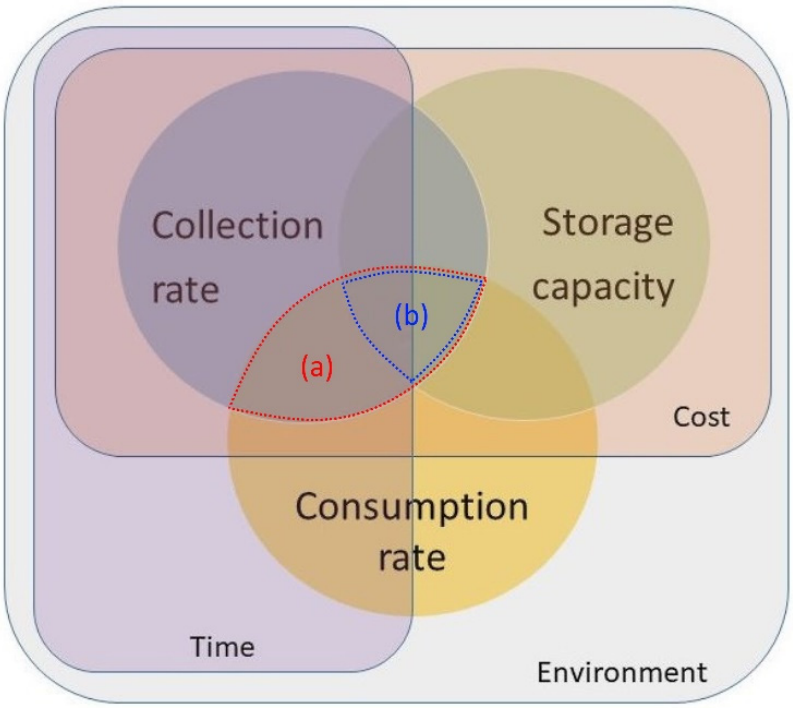


Figure 8. Interactions between parameters that affect plant growth and water use on an allotment.

Region (a) is primarily affected by the environment (in particular precipitation). Region (b) is determined by the setup of the plot, with good water collection, storage, irrigation and plant selection region (b) can be increased. Based on future climate change predictions, (Table 1) [28,30] the importance of region (b) for crop growth is set to increase as elevated temperatures and reduced precipitation will (generally) lower the output of region (a) while potentially boosting the output of region (b). Optimizing region (b) is vital to combat climate change through increased water resilience.

We have tried to draw all the elements of a water-efficient and climate change resilient allotment site, together with elements that we believe will promote accessibility, community spirit and mental wellbeing together into one design.

We envisage an allotment site (Figure 9) with a range of different sizes of plots, arranged in groups of 4–6 around a shared water collection point (Section 5) incorporated into an awning and bench. Excess rainwater is led, perhaps via French drains (File S3), to

a boggy area or pond that provides a focus for wildlife. The site's main paths follow the ground contours to reduce run-off and encourage infiltration (Sections 6 and 7), and will help maintain and increase region (a) in Figure 8 above. Made-up paths coming from a central hardstanding will separate groups of plots. Well-maintained paths, wide enough to allow wheelbarrow or wheelchair movements, and which follow the contours of the site, separate individual plots. Small plots and raised beds facilitate the grouping of plants with similar watering needs, the use of trickle or drip irrigation and the use of mulches, so that water can be used most efficiently. The hardstanding will be the site of a communal hut and toilet, drop off area for bulky materials like compost and also be surrounded by a mixture of raised planters and small beds suitable for wheelchair users or others with limited mobility. Some of the smaller plots could be dedicated to flowers to encourage pollinators. Close to this central area will be an area where children could play. The site requires vehicular access; to encourage visits by schools or groups with special needs this needs to be suitable for bus/coach. Site design can be adjusted to fit the topology of the ground. Ideally, the site is located on a very gentle south-facing slope with drainage or wetland to the south.

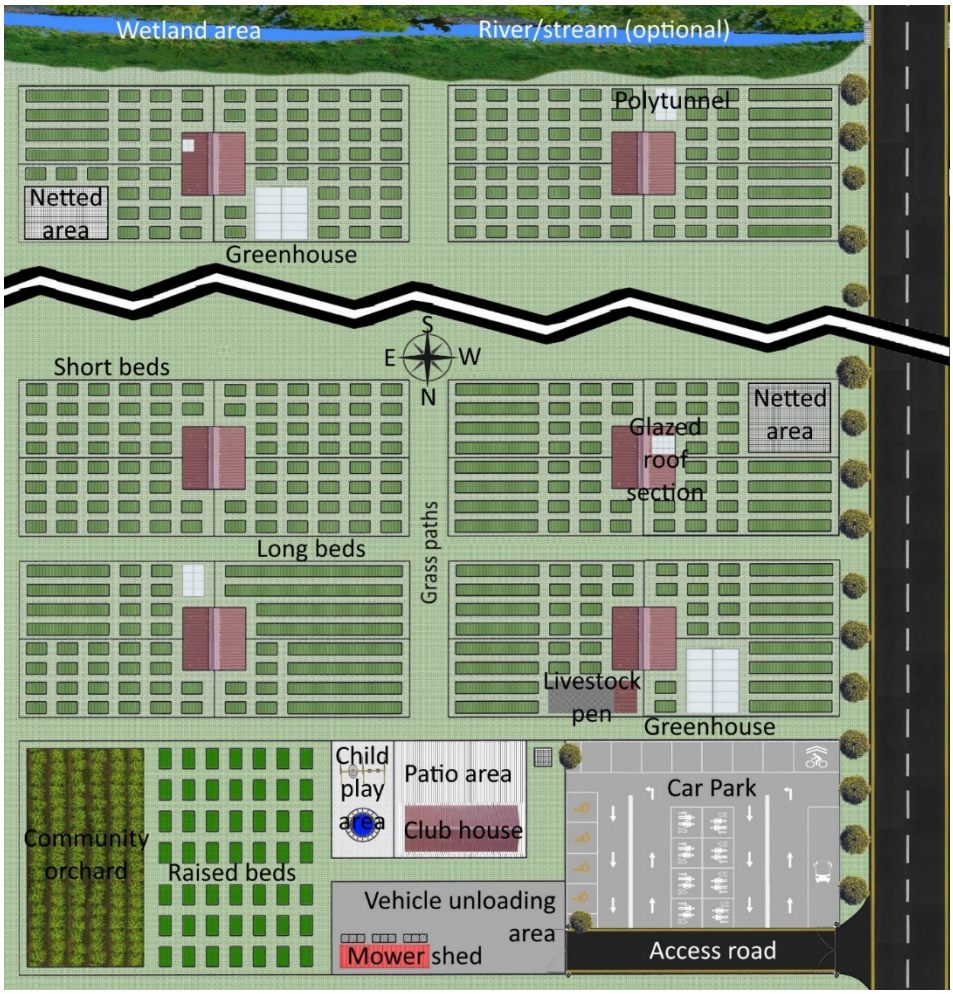


Figure 9. The allotment site of the future optimized for water efficiency.

The site facilities can be broken down into three groups:

(1) Shared buildings: communal building, compost toilet and handwashing facility, mower/power tools shed.

(2) Shared areas: communal patio, communal orchard, children play area, compost bays, unloading area for vehicles (deliveries of manure), car park (for bicycles, cars and optional bus/coach), optional raised beds for disabled and school use.
(3) Individual plots: short and long beds, optionally raised beds for less able, polytunnels/greenhouses, netted area, livestock pens.

The suggested layout is a balance between many factors. The car park is located at one end to separate people and vehicles. On larger sites, the shared facilities and car park could be located in the middle to reduce the maximum distance from plots to central facilities. The compost toilet is located close to the clubhouse and car park to maximize access to all. The children's play area is near the communal building and visible from most of the site. The manure bays are positioned away from plots and clubhouse to avoid unpleasant odours. The mower shed (metal shipping container) is located away from other structures for fire safety. Plot holders can customize their plots to match what they would like to grow (e.g., vary the ratio of short and long beds), adding greenhouses, polytunnels, netted areas or livestock pens as required. The size of the site can be easily adjusted to match requirements by changing the total number of plots in multiples of eight (as indicated by the zig-zag line).

9. Conclusions

We asked, how allotment plots and an allotment site might be organized if water use is taken as the starting point. The physical characteristics of this allotment site for the future (Figure 9), combine current knowledge to make a site that will be resilient to future climate change, particularly reduced summer rainfall and higher temperatures. The design encourages the natural infiltration and storage of rainwater within the soil by having paths laid out along the contours, and facilitates the use of bulky manures to improve soil structure and hence, soil moisture capacity (region (a) in Figure 8), thus reducing demand for applied water. The division of plots into smaller beds (Figure 6) makes it easier to implement water-efficient growing techniques. Some of these techniques, such as increased plant density and use of directed watering, allow more crop to be produced for the same amount of water and others, such as the use of winter-sown and widely spaced plants reduce the need for watering. All of these techniques help the grower to reduce demand for applied water (consumption rate in Figure 8) during the summer when, in the future, rainfall is likely to be reduced [28]. Estimates of potential demand for water and information about actual water use by allotment gardeners were used to decide the volume of water that might need to be collected and stored. The grouping of plots and use of shared water harvesting areas increase the collection and storage area available (region (b) in Figure 8). The large reservoir of stored rainwater (8000 L per plot) is sufficient to supply up to 200 L per day for more than a month and will mitigate against projected increases in temperature and evapotranspiration and decreases in summer rainfall.

Allotment growing provides many people with physical activity, brings them closer to nature and has a positive effect on mental health and wellbeing. Our design considers the importance of accessibility and the social and emotional aspects of community gardening. The provision of a toilet, raised planters, and paths that are wide enough for a pram or wheelchair will make the site attractive to families and people with mobility problems. The central community hub, or shared space, within the allotment design will encourage the building of an inclusive community where people of all socio-economic and cultural backgrounds, gender and age can come together to share knowledge and experience of gardening [6,7,12–15]. By making the site accessible and attractive, it would likely be used for more of the time, and this would help to deter vandalism. Promotion of consumption of home-grown fruit and vegetables will help reduce the UK's dependence on imports of fresh food from countries that are vulnerable to the effects of climate change and where water is a scarce resource [9–11]. These benefits would be on top of the already demonstrated benefit of allotment gardening in reducing food waste, encouraging a varied diet with fruit and vegetables and improving physical and mental health.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/w13111457/s1, File S1. Online resources with guidance and advice on watering and crop growth. File S2. Livestock on allotments. File S3. French Drains.

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Appendix A. Estimation of the Amount of Water Needed to Water Established Crops on an Allotment during the Summer

Appendix A.1. Background

The amount of water needed for watering plants on an allotment will vary with local conditions (soil type, topography and climate), type of plant and the time of year. We have made an estimate of how much water might be needed, on an allotment in the UK, allowing for predicted changes in climate. This section gives some background to the assumptions made in our calculations and is not intended to be a detailed review of plant-soil water relations; this topic is covered in more detail elsewhere [29,41,49,73,95–100].

Many plants are more than 90% water [100]; any reduction in water supply has negative effects on many plant processes including nutrient uptake, photosynthesis, respiration, and development and thus growth [95,96,100,101]. Plants take up water from the soil and it is lost, to the atmosphere, through transpiration via the stomata in the leaves and direct evaporation from the leaf surface [99,100]. Water lost at the leaf surface must be replaced by water taken up from the soil, creating a continuous stream of water, the transpiration stream that helps to keep leaves cool by evaporation, provides water for use in photosynthesis and transports mineral ions around the plant [100]. Water potential [95,100] is used to describe the free energy levels of water in soil, plants and the atmosphere. As water moves from the soil, through the plant, to the atmosphere it moves from high to low water potential [73,95,102] and this energy gradient drives the movement of water. If water uptake from the soil is less than water loss from the leaf surface the plant water potential will increase and water stress may occur. When plants are water-stressed, the stomata in the leaf surface close and the rate at which water is lost to the atmosphere slows. If the rate of water loss remains above the rate of supply from the soil, water will be lost from the plant cells, starting with those in the leaf [103]. When the cells lose water they become less turgid and the plant will wilt. In the UK, during hot sunny weather, large-leaved plants often wilt in late afternoon but during the night when it is cooler, and loses of water to the atmosphere less, are able to absorb sufficient water from the soil to recover. However, if the plant cannot absorb enough water from the soil to regain turgor, wilting will be permanent and the plant will die.

Soil moisture potential controls the ability of the plant to take up water [73,95,100]. A soil containing the maximum amount of water that it can hold under the influence of gravity is said to be at field capacity; the soil water potential is low and plants can easily take up water [73]. As water is removed the soil water potential increases and it becomes increasingly difficult for plants to take up water, and they may wilt during the day and recover at night. Once the soil moisture potential reaches around 1.5 MPa plants are unable to take up water, this is the permanent wilting point [95,100,102] The amount of water held between field capacity and permanent wilting point is the plant available water, [73,97] (Section 6). The amount of plant available water in the soil depends on the proportions of clay, sand, and silt, and on the soil structure, and can range from as little as 25 mm per metre depth on some sandy soils to 250 mm per metre on some clay soils [103]. In our calculation, below, we use 120 mm per metre; the value for a silty clay soil [45]; in UK silty clay soils are often called silty clay loams [75] and are considered good for growing garden vegetables [104].

Table A1. UK average seasonal rainfall totals (1981–2010) from Kendon et al. 2019 [63].

	Winter	Spring	Summer	Autumn
Rainfall (mm)	329	237	240	343

In 2018, annual rainfall averaged across the UK was 1056 mm [63] but the amount of annual rainfall ranges from >3000 mm per year, in parts of the Lake District and Western Highlands, to <500 mm per year, in parts of Essex, Suffolk and Cambridge [63]. In the UK, more rain normally falls during the winter and autumn, (Table A1) when demand for water by plants is low. In the decade, 2009–2018, UK winters have been 5% wetter than 1981–2010 and 12% wetter than 1961–1990 [63], and winter rainfall is likely to increase in the future (Table 1) [28,30].

Evapotranspiration (ET) is the process in which water moves from the Earth's surface into the atmosphere by a combination of evaporation from the soil surface and evaporation from the surface of plants plus transpiration by plants. ET is dependent on many factors including type of vegetation, amount of ground covered by vegetation, weather, soil moisture, local topography [98] and can vary widely between years, seasons and from one day to the next [29,105,106]. ET is difficult to measure [49]. ET can be determined experimentally using lysimeters in which the amounts of water taken up and supplied can be measured, estimated from calculations of the crop energy balance or estimated from measurements and calculation of soil moisture balances but all of these methods require specialized equipment [49]. ET values are usually calculated, from meteorological data (radiation, temperature, humidity and wind speed) [29,49,106]. There are many different methods of calculating ET [105], the most widely used is the Penman—Monteith equation [49,105,107]. The calculated values are potential evapotranspiration from a hypothetical short (0.12 m) grass surface when the water supply is unrestricted. Actual values of ET can be very different from the potential values [49,99,107]; closely spaced plants, especially if they are tall and have greater surface roughness than grass can have much higher values of ET than widely spaced short plants [49]. If the soil is dry and/or the plants are water-stressed (stomata in the leaves closed) actual ET may be less than the calculated ET [49]. Different types of vegetation have different rates of evapotranspiration, and these rates are different at different stages of development. The crop coefficient (Kc) can be used to adjust the value estimated from the Penman-Monteith calculation [49]. The crop coefficient is calculated by comparing ET from the Penman-Monteith equation with measured crop ET. In semi-arid regions, where crop production relies on irrigation but water supplies are limited, considerable effort has been made to understand how Kc changes throughout the year and how ET varies from year to year [108].

In the UK, the average annual potential ET is 650–700 mm (1961–2012 average annual estimate, Penman-Monteith method) [105], this is equivalent to 650–700 L m^{-2}. In the UK, potential and actual ET values show high seasonality, values of potential ET in the summer are about six times higher than those in the winter [29] and are usually highest between May and August when crops are growing rapidly and temperatures are higher. Typical daily values of potential ET (Penman-Monteith method) for the UK range from 0.5–1 mm per day in Nov, Dec, Jan and Feb to 3–3.5 mm per day in May, June, July and August [105]. There is a gradient of ET across Britain. Values of potential ET are lower in the Northwest and highest in the Southeast [103]; actual ET in the Northwest is similar or higher than potential ET but in the drier Southeast actual ET is often below potential ET because it is limited by soil moisture [29,105]. During the warmest months, potential ET (Penman-Monteith method) in Central England can be over 100 mm per month [106]. Values of potential and actual ET, in the UK, increased between 1961 and 2015, and, by the 2080s, are predicted to increase by between 12% and 56%, with the greatest increases in the winter [29,105,107]. Work at the former National Vegetable Research Station (NVRS, now part of Warwick University, UK), indicated that a well-grown crop that completely covers the ground can remove about 5.4 L m^{-2} day^{-1} of water during dry sunny weather [44]. This figure is higher than the values for potential ET above [105] because it refers to large leafy vegetables growing with sufficient water to meet maximum transpiration needs.

Appendix A.2. Calculation of the Amount of Water That Might Be Needed to Water Plants in UK during the Summer Months

We have used two values of evapotranspiration in our calculations: 5.4 L m^{-2} day^{-1} [44] and 4.025 L m^{-2} day^{-1} (based on a potential ET value of 3.5 L m^{-2} day^{-1} [107] multiplied by the crop coefficient (Kc) for potatoes [109].

The value of 5.4 L m^{-2} day^{-1} [44] is high but if rates of ET increase as predicted [29,107] may become the average. We have assumed that the ground surface is completely covered by the crop and it is at the stage of development when it has the highest demand for water. We have based our calculation on a three-month period when ET is above precipitation [106,107], and assumed that ET is at the maximum rate throughout this period. We do not know how potential and actual rates of ET will change in the future and have chosen to use these maximum values to give some degree of future-proofing in our estimate of water requirements:

$$\text{ET} = 5.4 \text{ L m}^{-2} \text{ day}^{-1} \quad \text{(A1)}$$

If we assume that 150 m^2 of ground are covered in crops [8] this is 811.5 L per day, or 73,000 L (811.5 × 90) or 7.3 m^3 over a three-month period.

73,000 L of water is equivalent to 486.9 L m^{-2} or 486.9 mm.

$$\text{ET} = 4.025 \text{ L m}^{-2} \text{ day}^{-1} \quad \text{(A2)}$$

If we assume that 150 m^2 of ground are covered in crops [8] this is 603.7 L per day, or 54,300 L (603.7 × 90) or 5.4 m^3 over a three-month period.

54,300 L water is equivalent to 362.25 L m^{-2} or 362 mm.

If on average 240 mm rain falls in the summer months (Table A1), there may be a potential summer shortfall of about 120–250 mm or 120–250 L m^{-2}. Over 150 m^2 this equates to 18,000–37,500 L.

If we assume soil reserves can supply 120 mm water [49], up to 19,000 L may be needed for watering over the summer growing period. This is roughly 200 L per day per plot (assuming 150 m^2 of a 250 m^2 plot is covered by crops). 19,000 L is slightly more than the volume of water currently used by some plot holders [65].

Appendix B. Example Calculation of the Amount of Water That Could be Collected from a Roof

Annual volume of rainwater that could be collected = Annual rainfall (m) × collection area (m^2) × 0.8.

For example, for a shed or greenhouse of 2 × 3 m (6 m^2 area) and 800 mm annual rainfall.

Annual volume of rainwater that could be collected = 0.8 m × 6 m^2 × 0.8 = 3.84 m^3 (3840 L)

* Annual average rainfall for a specific area can be obtained from the Met Office website (https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/rain/how-much-does-it-rain-in-the-uk, accessed on 5 February 2021).

Normally about 80% of collected water is used (0.8 in the calculation above), as some will be lost in storage due to evaporation.

Appendix C. Example Design of Water Collection Structure Using Scaffold Poles for the Framework

Scaffold poles are normally 6 m in length and 48.4 mm in diameter. To simplify construction the base could be reduced (from 8 m × 8 m) to 6 m × 5.64 m. This allows: (a) single poles to span the full width & depth (b) two 3 m rafters can be made from one pole cut in half. The poles can be fastened together with standard scaffold brackets. The corrugated sheeting can be attached to poles with 'U' or hook bolts. Additional cross braces and ties are required depending on the site conditions (e.g., to cope with aerodynamic loading). An example design (with 20° pitch) is shown.

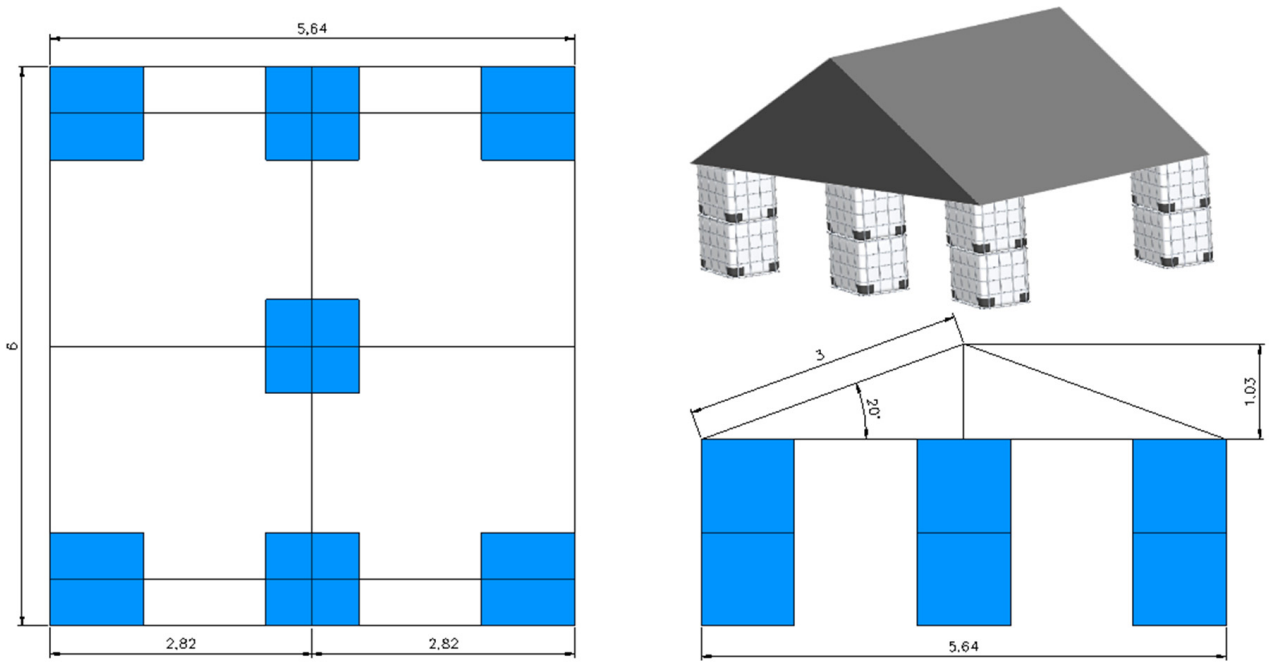


Figure A1. Example design of water collection structure using scaffold poles for the framework.

As the rainwater collection area has been reduced from 64 m^2 to ~34 m^2 the number of IBCs has been reduced from 16 to 14 and their locations adjusted to provide the poles with additional end support under the ridge.

Appendix D. Watering Requirements (in the UK) of Some Widely Grown Outdoor Vegetables

Table A2. Watering requirements in the UK of some widely growing outdoor vegetables (based on Salter, Bleasdale et al., [44]). Always direct water to the base of the plants so that it can penetrate into the soil rather than be lost through evaporation.

Type of Crop	Crop	How Much Water to Apply	When to Water If No Watering Limitation	When to Water If Watering Is Restricted	Comments
Leafy vegetables	Cabbage Kale Lettuce Spinach	11–16 L m^{-2} once established	Each week	2 weeks before cutting 22 L m^{-2}	Overwatering will cause the heads to burst
	Brussels sprouts	150 ml per plant per day when transplanted	No need to water after established except in very dry years		
Fruiting vegetables	Peas Broad beans French beans Runner beans	5–11 L m^{-2}	Twice each week throughout flowering and pod-growing periods	Once as first flowers open, and once as pods swell	Misting or spraying the flowers does not improve number of pods that set
	Tomatoes Marrow cucumber	10 L m^{-2}	Twice each week during flowering and fruit forming	Twice weekly during flowering and fruiting but can sink a pot into ground close to roots to ensure maximum amount of water is directed to the root	
Root vegetables	Carrot Parsnip Beetroot radish	5 L m^{-2} when young 16–22 L m^{-2} when storage roots growing	Every two to three weeks, before soil gets too dry		Watering (or rain) after a prolonged dry spell can cause the roots to split
Potatoes	The watering requirements of potatoes depend on the type (early or main crop), and variety. The Royal Horticultural Society is a good source of general guidance.				https://www.rhs.org.uk/advice/grow-your-own/vegetables/potatoes, accessed on 4 February 2021

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