Rainwater harvesting (RWH) tool for soft fruit production in polytunnels

User guidance manual



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Background

Soft fruit is a high-value crop sector in the UK with the majority of production grown at field-scale under protected (polytunnel) conditions. In terms of geographical distribution, most production is concentrated in the southeast, east, and West Midlands in England and in southeast Scotland (Rey et al., 2017). Many catchments where soft fruit are grown in England are classified by the Environment Agency (EA) as being either “over-abstracted” and/or “over-licensed” (Knox et al., 2009). In Kent, soft fruit production under polytunnels is an important part of the rural economy, and entirely dependent on irrigation. However, during the growing season, polythene structures also have potential to accentuate runoff leading to localised flooding and soil erosion. In some catchments they have also been reported to cause high silt and nutrient loads from polytunnel runoff into local watercourses.

In recent years there has been a growing interest in the potential for rainwater harvesting (RWH) systems to be used in polytunnel soft fruit production to reduce dependence on public mains water supplies, to reduce the need to treat water for irrigation and to reduce runoff risks. Working with growers and key stakeholders in Kent, and with funding from Kent County Council, researchers from Cranfield University have designed and developed a simple Microsoft Excel-based tool to help soft fruit growers and farm business advisors evaluate the hydrological performance and water storage effectiveness of RWH systems to support decision making regarding their viability for protected cropping. The tool was designed to be simple and intuitive to use and requires only a very limited set of farm level input data.

This manual provides step by step guidance on how to use the RWH tool and how to interpret the outputs. The tool operates on standard specification desktops and laptops and only requires the user to have Excel installed on their computer and to have a basic understanding of how to navigate around Excel. A description of the RWH modelling components and assessment metrics are provided in the Annex.

RWH tool functionality

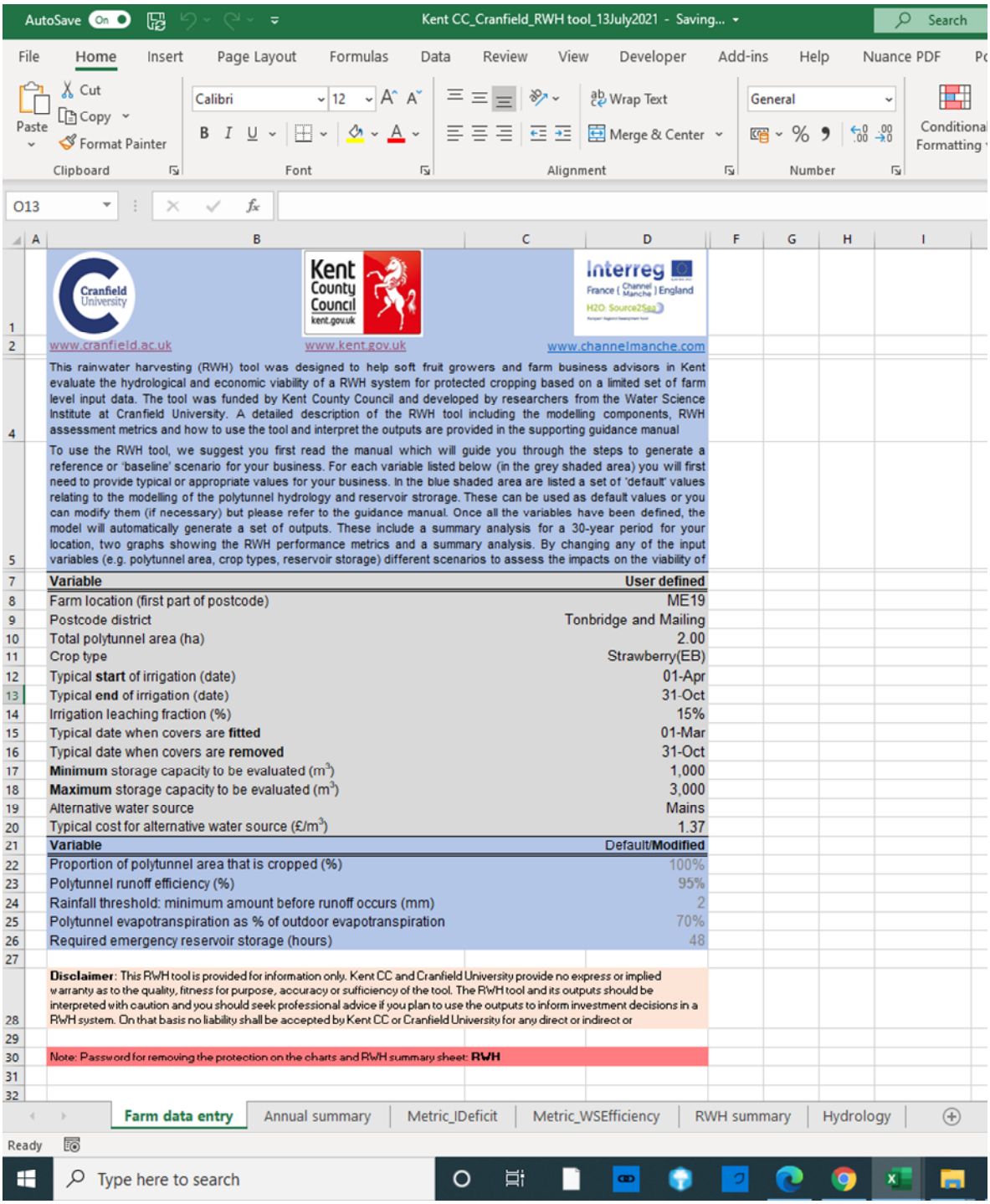
The RWH tool was designed to assist horticultural businesses improve their decision-making regarding how best to incorporate RWH into their water management practices. The tool will support you in calculating the most effective RWH system for your circumstances, taking into account local climate as well as farm information on cropped areas, crop types and available water storage. The RWH tool can be used to:

- assist farmers with existing RWH installations to evaluate the relative performance of their systems and to identify measures to improve rainwater self-sufficiency;
- enable farmers that do not have RWH systems to evaluate potential irrigation water resource benefits, including design and management options, and mains water saving costs, and;
- assist others involved in design of RWH systems for new polytunnel developments to make informed decisions regarding trade-offs between RWH performance and water storage capacity to recommend systems best suited to local circumstances.

Getting started (overview)

Download the Excel workbook “Cranfield RWH tool_2021” to your computer and open the file by double clicking on the filename or opening it directly from Excel. Excel may show a “Security warning” that macros have been disabled. This refers to an automated set of actions within the RWH tool that perform some of the calculations. If this warning appears, please click on “Enable Content”.

The RWH tool is a workbook with 5 separate sheets, each labelled with a grey tab at the bottom of the page (Farm data entry; Annual summary; Metric_IDeficit; Metric_WSEfficiency, and RWH Summary) as shown in the panel below. Of the 5 worksheets, 4 worksheets (Annual summary; Metric_IDeficit; Metric_WSEfficiency, and RWH summary) are password protected and cannot be edited.



To use the RWH tool, the user first needs to complete the Farm data entry form.

For each variable in the **grey shaded area** you will need to provide appropriate values for your business.

In the **blue shaded area** are listed a set of 'default' values relating to the modelling of the polytunnel hydrology and reservoir storage. You can leave these as ‘default values’ or you can modify them based on your own experience or technical knowledge.

Once all the variables have been defined in the grey shaded box, the model will automatically generate a set of RWH outputs.

These include analysis based on 30 years of recent daily weather data for your location (Annual summary tab), two graphs showing the RWH performance metrics (Metric_IDeficit and Metric_WSEfficiency) and an overall summary analysis (RWH summary).

By changing any of the input variables on the Farm data entry sheet (such as the polytunnel area, the crop type, reservoir storage) different scenarios to assess the impacts on the viability of a RWH system for your business can be evaluated.

The following pages provide a step-by-step guide to completing the Farm Data entry sheet and how to interpret the results (annual summary and RWH metrics).

The application of the RWH tool is demonstrated with reference to an imaginary soft fruit farm in Rochester, Kent

Farm data entry

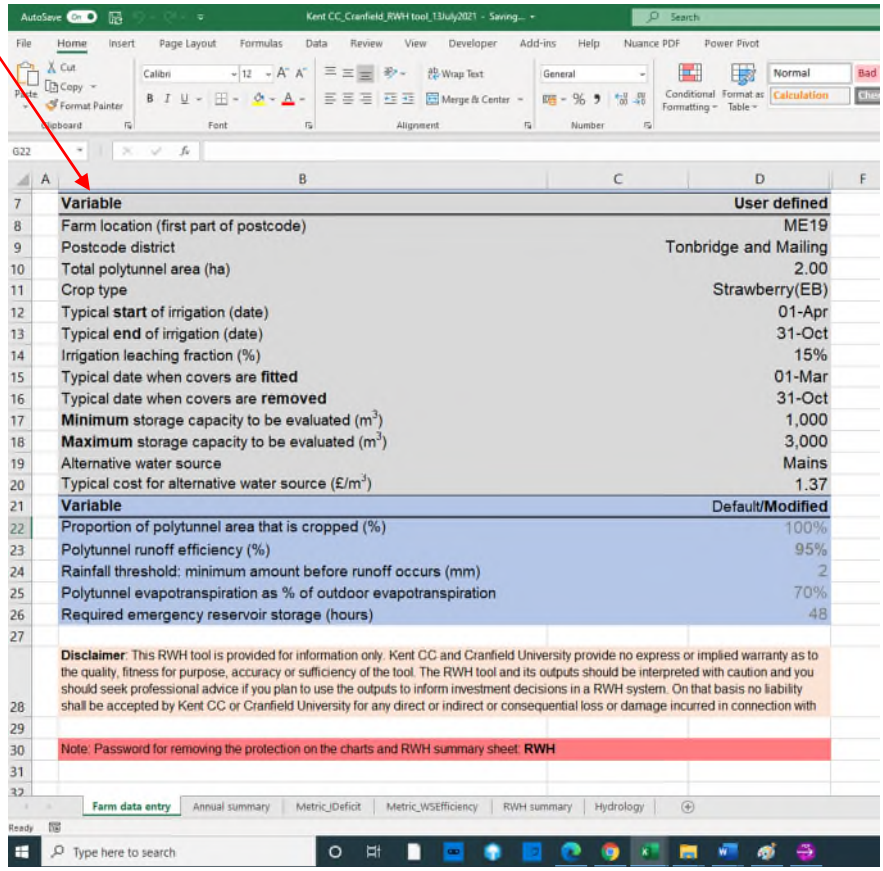
The first step is to select suitable data values (user-defined and default variables), which can be different for different farm businesses and their cropping type and location. The figure below shows the “Farm data entry” worksheet for an imaginary farm business at Rochester, Kent. The details of the user-defined and default variables and their explanation are provided in Annex 1.

Grey shaded area

For each variable you will need to provide appropriate values for your business. These include:

Farm location. Type in the first half of your postcode or select the postcode from the drop-down list and the district will automatically be retrieved. The district is used to retrieve appropriate long-term weather data for your site.

Enter your **Total polytunnel area (ha)**



	Variable	User defined
8	Farm location (first part of postcode)	ME19
9	Postcode district	Tonbridge and Mailing
10	Total polytunnel area (ha)	2.00
11	Crop type	Strawberry(EB)
12	Typical **start** of irrigation (date)	01-Apr
13	Typical **end** of irrigation (date)	31-Oct
14	Irrigation leaching fraction (%)	15%
15	Typical date when covers are **fitted**	01-Mar
16	Typical date when covers are **removed**	31-Oct
17	**Minimum** storage capacity to be evaluated (m^3)	1,000
18	**Maximum** storage capacity to be evaluated (m^3)	3,000
19	Alternative water source	Mains
20	Typical cost for alternative water source (£/m^3)	1.37
21	**Variable**	**Default/Modified**
22	Proportion of polytunnel area that is cropped (%)	100%
23	Polytunnel runoff efficiency (%)	95%
24	Rainfall threshold: minimum amount before runoff occurs (mm)	2
25	Polytunnel evapotranspiration as % of outdoor evapotranspiration	70%
26	Required emergency reservoir storage (hours)	48
27		
28	**Disclaimer**: This RWH tool is provided for information only. Kent CC and Cranfield University provide no express or implied warranty as to the quality, fitness for purpose, accuracy or sufficiency of the tool. The RWH tool and its outputs should be interpreted with caution and you should seek professional advice if you plan to use the outputs to inform investment decisions in a RWH system. On that basis no liability shall be accepted by Kent CC or Cranfield University for any direct or indirect or consequential loss or damage incurred in connection with
29		
30	Note: Password for removing the protection on the charts and RWH summary sheet: **RWH**	
31		

Using the dropdown menu select **Crop type**. Three options are available including ever bearer strawberry (EB), June bearer strawberry (JB), raspberry. Only one crop type can be selected.

For the crop type selected, enter the **Typical start of irrigation (date)** and **Typical end of irrigation (date)***.

Based on the crop type and your irrigation scheduling approach, enter the **Irrigation leaching fraction (%)**.

For your crop type, enter the **Typical date when covers are fitted** and **Typical date when covers are removed***.

The RWH tool assumes that rainfall collected from the polytunnel area will be stored in a new reservoir. The tool provides output data and metrics for a range of storage capacities, so you need to define what should be the “**Minimum storage capacity**

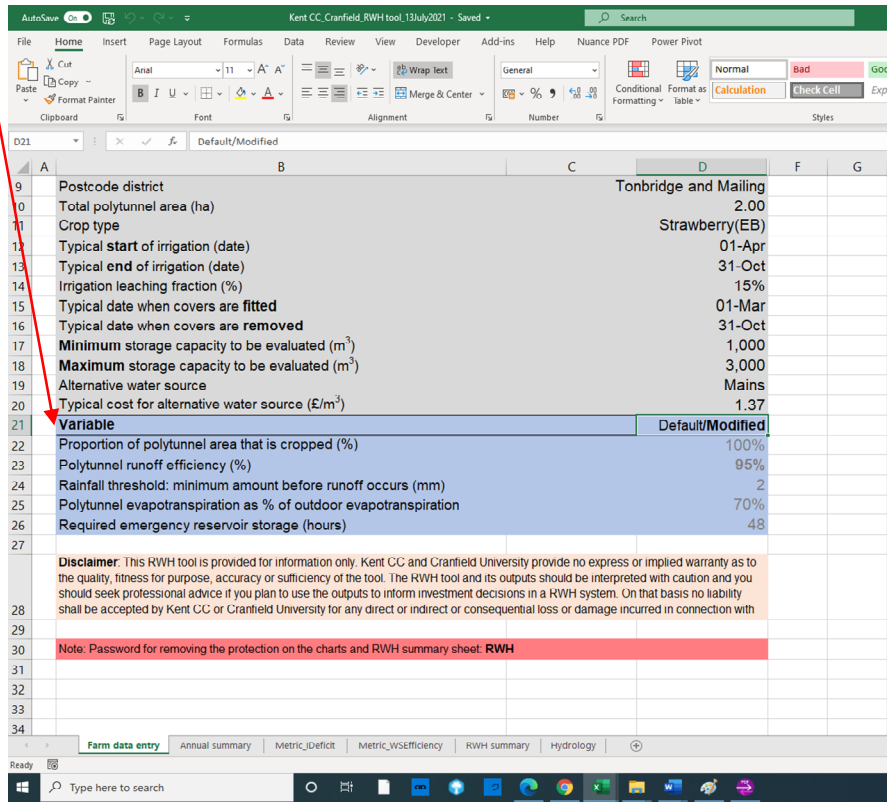
* Enter dates in the format DD/MM/YYYY (e.g. 01/04/2020). NB you can use any year.

to be evaluated (m^3) and the **Maximum storage capacity to be evaluated (m^3).** These values can be changed after you have run the model for the first time.

Any shortfall in water collected from the RWH system to meet irrigation demand is assumed to be met from either public mains supply, surface water abstraction (summer), or an existing reservoir (lined or unlined). Using the dropdown menu, choose your appropriate **Alternative water source**. The typical cost for this alternative water source is automatically estimated, but it can be changed if you know the real cost.

Blue shaded area

A set of 'default' values are provided in this area. These relate to the modelling of the polytunnel hydrology and reservoir storage. These can be left unchanged or you can modify them, if necessary. If the default values will be modified, the values will change into bold.



9	Postcode district	Tonbridge and Mailing
10	Total polytunnel area (ha)	2.00
11	Crop type	Strawberry(EB)
12	Typical **start** of irrigation (date)	01-Apr
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30	Note: Password for removing the protection on the charts and RWH summary sheet: **RWH**	
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Proportion of polytunnel area that is cropped (%) The RWH tool assumes the cropped area to be the same as the polytunnel roof area (100%) but this can be revised.

Polytunnel runoff efficiency (%) This value is used to calculate the potential volume of rainwater that can be usefully collected from the polytunnel area. It is a function of reliable local rainfall and system configuration, as well as factors influencing runoff such as the polytunnel structure and size, slope, and the duration over which the polytunnel covers are used. See Annex 1 for further details.

Rainfall threshold: minimum amount before runoff occurs (mm) Not all rain that lands on a polytunnel can be collected, depending on the duration, intensity and amount of rainfall. Very small amounts of rain will not result in any runoff due to storage on the polytunnel, wind drift and evaporation. In this tool it was assumed that days with less than 2mm will not generate any runoff.

Polytunnel evapotranspiration as % of outdoor evapotranspiration: Crops grown under plastic are subject to different (usually lower) levels of evapotranspiration (ET) compared to crops grown outdoors. Plastic covers affect the incoming solar radiation, temperature, windspeed and humidity. It is therefore important to modify the reference evapotranspiration in the weather data to represent the conditions inside the polytunnel. See Annex 1 for further details.

Required emergency reservoir storage (hours) Polytunnel cropping systems are highly vulnerable to any disruption in water supply for irrigation. It is therefore prudent for RWH systems to incorporate some temporary, short-term storage capacity to buffer against a supply failure. For a given storage capacity, the RWH model therefore calculates 2 days (48 h) storage based on peak irrigation demand. This value was derived from interviews with irrigation consultants and suppliers to not allow the reservoir storage to go below 2 days of peak gross water demand[†]

[†] "Gross water demand includes" the crop water requirement plus the leaching requirement.

RWH analysis: Annual summary

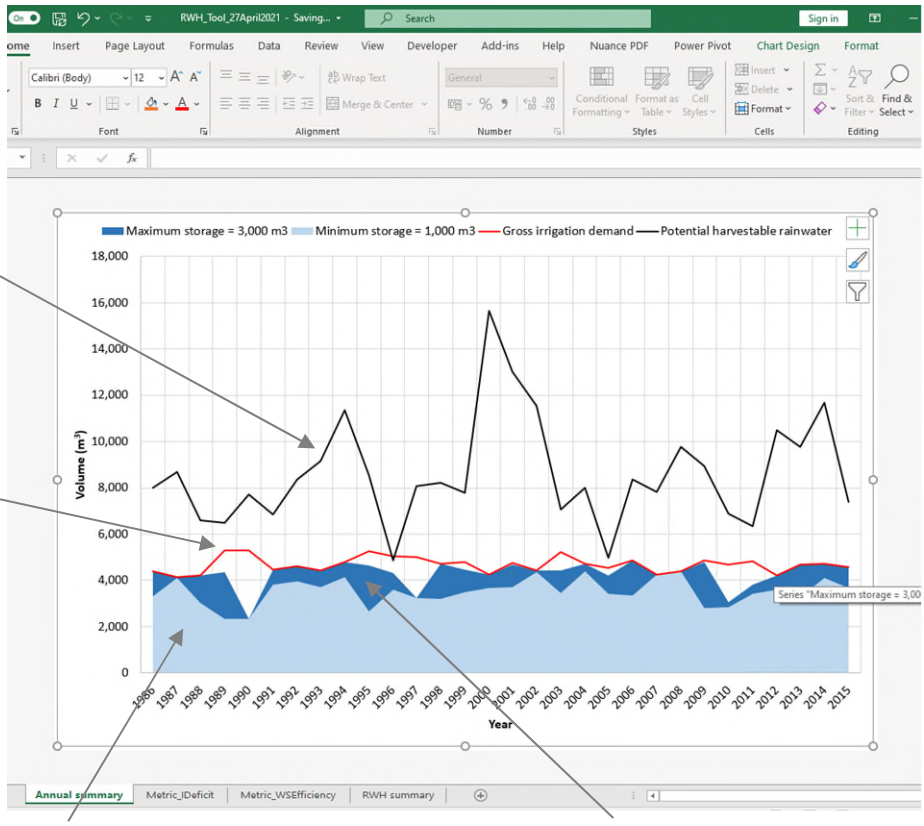
Once all the user-defined variables have been added in the Farm data entry sheet, the RWH tool will automatically generate a set of outputs. These include a summary analysis for a 30-year period (1986-2015) for the farm location. An explanation of how the RWH tool uses the long-term daily weather data to drive a polytunnel hydrology model and to calculate irrigation demand is given in Annex 2. An example output for the annual summary is shown in the panel below.

This provides an annual summary for four key variables.

Volume of potentially harvestable rainfall that could be usefully collected from the polytunnels (**black line**)

Volume of gross irrigation water demand (**red line**)

Volume of harvested rainwater used to meet irrigation demand for the selected minimum (**light blue shaded area**) and maximum (**dark blue shaded area**) storage capacities.



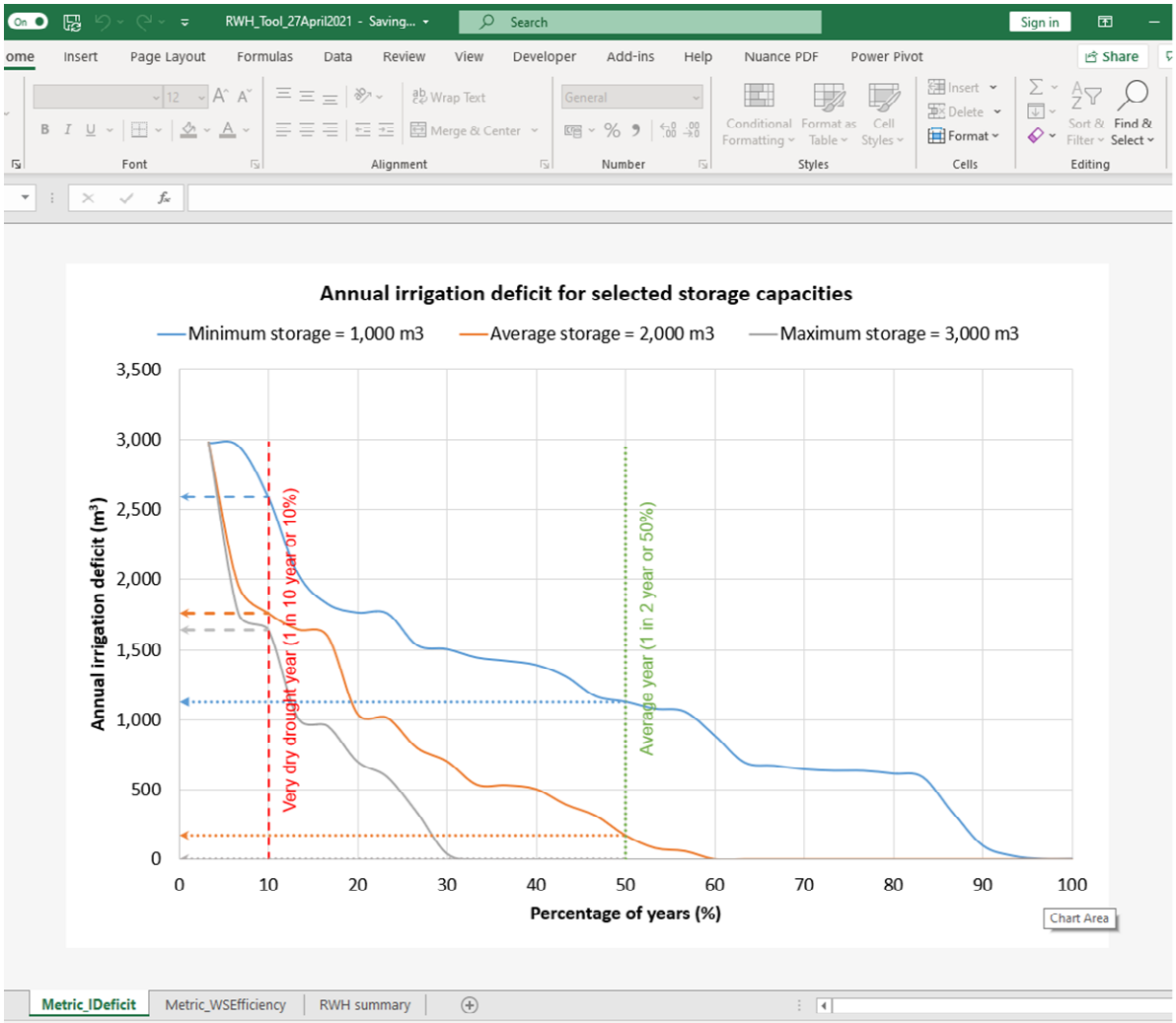
The figure shows that this farm has potential to collect sufficient rainwater (**black line**) in all years as the potential volume harvested (between 5,000 and 16,000 m^3) is well in excess of irrigation demand (**red line**) which ranges between 4,000 and 5,500 m^3. However, with the minimum reservoir storage (1,000 m^3) the amount of water available fails to meet irrigation demand in most years.

The maximum reservoir storage (3,000 m^3) provides a higher degree of reliability and meets irrigation demand in many years, but there are still periods when there would be an irrigation deficit (shortfall between storage and irrigation demand) for example in 1988-1991, 1995-1998, 2003, and 2010-2011. In these years, the RWH system would be inadequate and an alternative water supply would be needed to augment the RWH storage.

The RWH tool could be re-run with a larger maximum storage capacity to remove these deficit years.

RWH analysis: Irrigation deficit (m^3)

Based on the data provided in the Farm data entry sheet, the RWH tool produces outputs for two key performance indicators. The first is the irrigation deficit (m^3), defined as the gross irrigation demand not met due to rainfall uncertainty and insufficient water available in the RWH storage reservoir. An example output for this irrigation deficit metric is shown in the panel below, together with an explanation on how to interpret the data.



This figure shows the cumulative probability (percentage of years) for the annual irrigation deficit metric based on 30 years of historical weather data, for three reservoir capacities (1,000, 2,000 and 3,000 m^3). The minimum and maximum capacities were defined on the Farm data entry sheet.

For a given reservoir capacity, the annual probability of an irrigation deficit can be identified. For example, for a 1,000 m^3 reservoir, the figure above provides a **green dotted line** at 50% (or 1 in 2 year) probability that there will be an annual irrigation deficit (shortage of water) of at least 1,200 m^3 shown by **blue dotted arrow**. For the larger (2,000 m^3) reservoir, the annual deficit would be at least 200 m^3 shown by **orange dotted arrow**.

The figure also provides the equivalent data for a more extreme drought year which would be relevant for RWH system or irrigation design purposes. This is shown as the **red dashed line** at the 10% probability level (or 1 in 10 year). For the largest

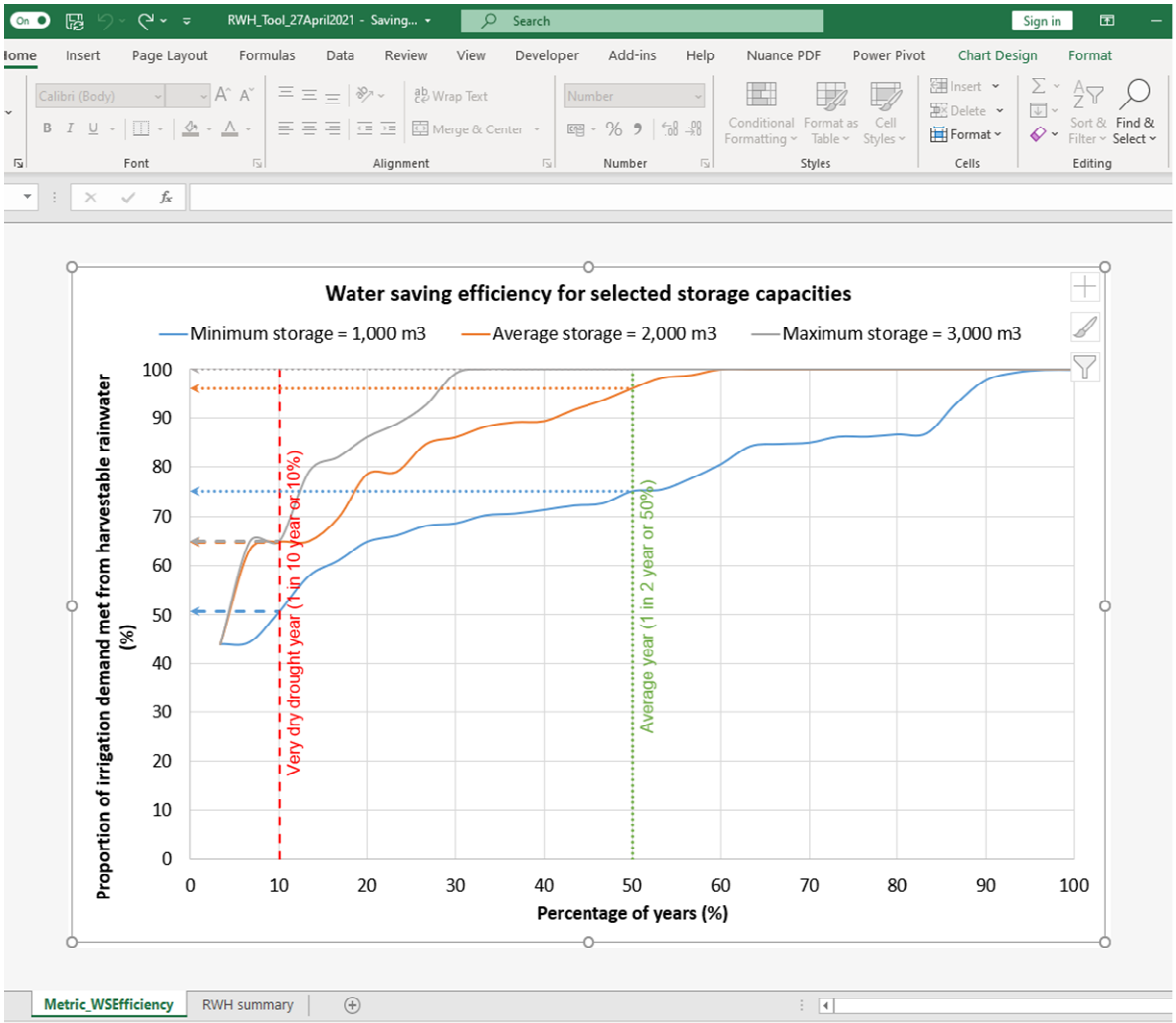
reservoir considered here (3,000 m^3) there would still be an irrigation deficit of at least 1600 m^3, as shown by the **grey dashed arrow**. So even the maximum storage reservoir in this example would be inadequate to meet gross irrigation demand, and a larger reservoir would be needed to reduce or remove any irrigation deficit.

The tool can be used to identify the optimum storage capacity to maximize the use of rainwater, eliminate any irrigation deficit and minimise the reliance (and cost) on an alternative water source to meet irrigation demand.

RWH analysis: Water saving efficiency

The RWH tool also produces a second key performance indicator termed *w*ater saving efficiency (%). This is defined as the total amount of water supplied from the RWH system as a percentage of the total amount of irrigation water required.

An example output for the water saving efficiency (%) metric is shown in the panel below, together with an explanation on how to interpret the data.



This figure shows the relationship between the percentage of irrigation demand met from the harvestable rainwater (%) and the percentage of years (%). As with the irrigation deficit metric, the data are based on 30 years historical weather and for three reservoir capacities.

For a given reservoir capacity and probability (percentage of years), the water saving efficiency can be identified. For example, for a 1,000 m^3 reservoir, on average (50% of years) the water saving efficiency is around 75%. For the largest (3,000 m^3) reservoir, on average the water saving efficiency is 100%.

However, in very dry drought years, the reliability or water saving efficiency declines, even for the largest reservoir.

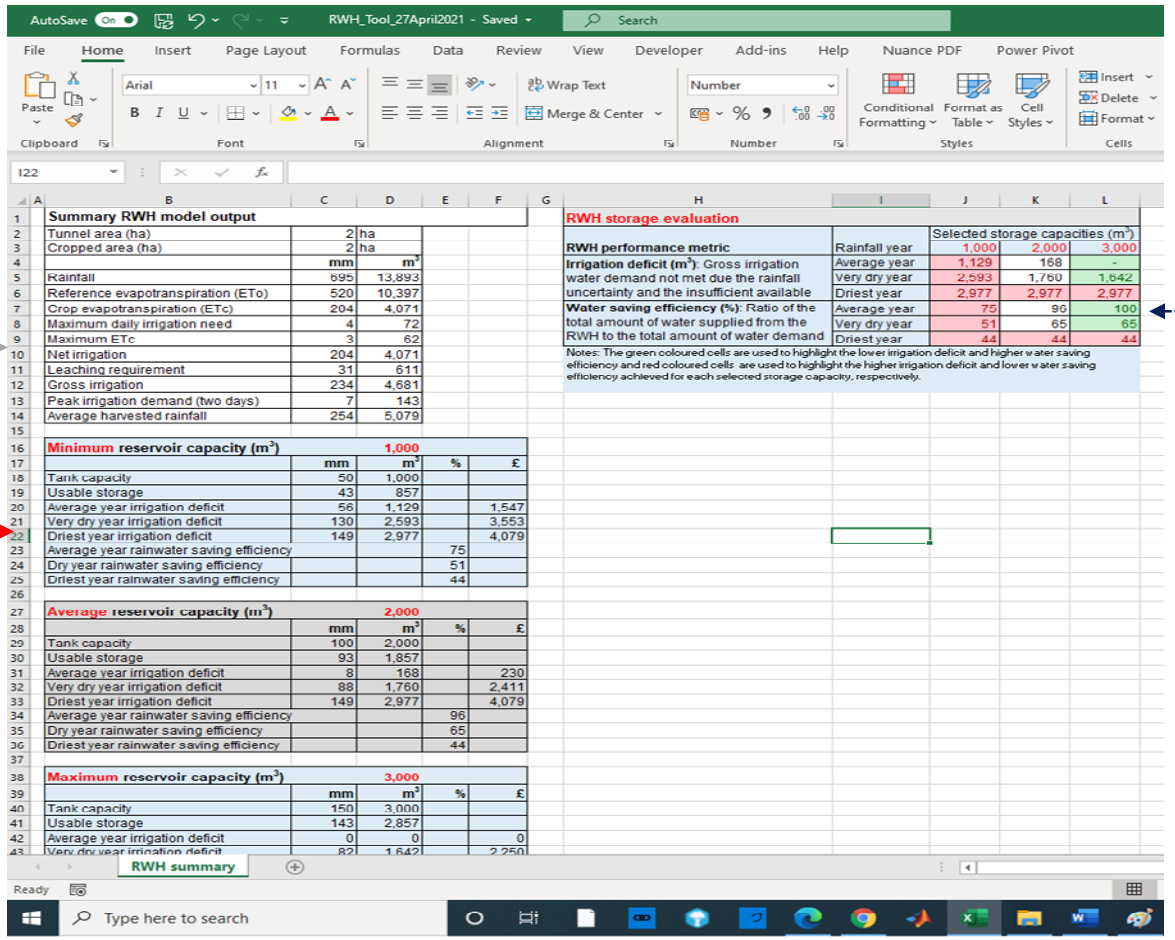
In 10% of years, or a 1 in 10-year drought event, the water saving efficiency for the RWH system with the largest (3,000 m^3) reservoir drops to 65%, and for the smallest (1,000 m^3) reservoir the efficiency is nearer to 50%.

This metric is therefore useful in understanding the trade-offs between the size of the reservoir storage, the reliability of the RWH system to meet crop irrigation demand, and the cost to augment supplies with an alternative water source.

RWH analysis: Summary

It is important for a farm business to critically evaluate the irrigation and water resource implications and economic viability of any potential investment in a RWH system. The final sheet in the RWH tool therefore provides a detailed summary of outputs from the RWH tool, including information on irrigation demand, statistics relating to different reservoir storage capacities, and two performance metrics. Data on the costs for augmenting any irrigation deficit with water from an alternative source of supply are also provided.

A typical output for the RWH summary is shown in the panel below, together with an explanation on how to interpret the data.



Summary RWH model output		
Tunnel area (ha)	2	ha
Cropped area (ha)	2	ha
	mm	m³
Rainfall	695	13,893
Reference evapotranspiration (ETo)	520	10,397
Crop evapotranspiration (ETc)	204	4,071
Maximum daily irrigation need	4	72
Maximum ETc	3	62
Net irrigation	204	4,071
Leaching requirement	31	611
Gross irrigation	234	4,681
Peak irrigation demand (two days)	7	143
Average harvested rainfall	254	5,079

Minimum reservoir capacity (m³)	1,000			
	mm	m³	%	£
Tank capacity	50	1,000		
Usable storage	43	857		
Average year irrigation deficit	56	1,129		1,547
Very dry year irrigation deficit	130	2,593		3,553
Driest year irrigation deficit	149	2,977		4,079
Average year rainwater saving efficiency			75	
Dry year rainwater saving efficiency			51	
Driest year rainwater saving efficiency			44	

Average reservoir capacity (m³)	2,000			
	mm	m³	%	£
Tank capacity	100	2,000		
Usable storage	93	1,857		
Average year irrigation deficit	8	168		230
Very dry year irrigation deficit	88	1,760		2,411
Driest year irrigation deficit	149	2,977		4,079
Average year rainwater saving efficiency			96	
Dry year rainwater saving efficiency			65	
Driest year rainwater saving efficiency			44	

Maximum reservoir capacity (m³)	3,000			
	mm	m³	%	£
Tank capacity	150	3,000		
Usable storage	143	2,857		
Average year irrigation deficit	0	0		0
Very dry year irrigation deficit	82	1,642		2,250

RWH storage evaluation		Selected storage capacities (m³)		
RWH performance metric	Rainfall year	1,000	2,000	3,000
Irrigation deficit (m³): Gross irrigation water demand not met due the rainfall uncertainty and the insufficient available	Average year	1,129	168	-
	Very dry year	2,593	1,760	1,642
	Driest year	2,977	2,977	2,977
Water saving efficiency (%): Ratio of the total amount of water supplied from the RWH to the total amount of water demand	Average year	75	96	100
	Very dry year	51	65	65
	Driest year	44	44	44

Notes: The green coloured cells are used to highlight the lower irrigation deficit and higher water saving efficiency and red coloured cells are used to highlight the higher irrigation deficit and lower water saving efficiency achieved for each selected storage capacity, respectively.

This summary sheet contains 3 main blocks of information which have been derived from the model based on the data provided in the Farm data entry sheet.

Useful summary details on rainfall and ET_o for your farm location, seasonal crop evapotranspiration, leaching requirements and irrigation demand are shown in the top left (white) panel. Values in mm and m^3 are provided.

For each reservoir storage capacity summary statistics are provided on the usable storage and the performance metrics (irrigation deficit and water saving efficiency) for an average, very dry (1 in 10 year) and the driest year. Costs (£) of an alternative annual water supply to offset the irrigation deficit are also provided.

The most important statistics are summarised on the right-hand panel. For each reservoir capacity, data for each of the two performance metrics (irrigation deficit and water saving efficiency) for each weather year (average, very dry and driest)

are provided. Colour coding is used to help the user identify the optimum RWH storge-reliability combination.

This summary enables farmers to identify the most effective RWH system for their circumstances, taking account of local climate variability as well as farm information on cropped areas, crop types and storage. Business case studies are provided to highlight the application of the tool.

RWH and climate change impacts

The United Kingdom Climate Projections 2018 (or UKCP18) provide the most up-to-date projections regarding how the UK's climate may change in the future due to greenhouse gas emissions. The probabilistic projections combine climate model data, observations and advanced statistical methods to simulate a wide range of climate outcomes for a range of greenhouse gas emission scenarios from RCP2.6 (low emissions scenario) to RCP8.5 (high emissions scenario). Broadly speaking, the emissions associated with the RCP2.6 scenario are comparable to those of the so-called 'Paris Agreement' to reduce greenhouse gas emissions; whilst RCP8.5 is comparable with current (pre-covid) global trends in greenhouse gas emissions.

The probabilistic projections provide a central (most likely) assessment of the change in each climate variable (given by the 50th percentile or median), but also an uncertainty range. Future changes in climate variables are, for a given emissions scenario, unlikely to be below the 10th percentile value and unlikely to be above the 90th percentile value.

Table 1 shows the projected changes in seasonal average precipitation and temperature in winter and summer under RCP2.6 and RCP8.5 in the 2050s (2040-2069) for south-east England relative to 1981-2010. This shows that:

- The magnitude of the projected changes in precipitation and temperature increase with increasing greenhouse gas emissions.
- Temperatures will tend to increase in all seasons, leading to increased evaporation from open reservoirs, increased reference evapotranspiration and increased irrigation water demand inside polytunnels.
- Precipitation will be expected to increase in winter (although there is small risk that it may decrease), providing increased potential for rainwater harvesting from permanent glasshouses.
- However, precipitation is expected to reduce in both spring and summer, although there is considerable uncertainty in the direction of change in spring. Nevertheless, the projections suggest that rainfall reliability for re-filling reservoirs in seasonal polytunnels will be reduced.

Table 1 Projected seasonal changes in seasonal average temperature and precipitation (10th, 50th and 90th percentile) under contrasting climate change projections for South East England (relative to 1981-2010) in 2050s (2040-2069)

Variable	Season	RCP2.6			RCP8.5		
		10th	50th	90th	10th	50th	90th
Rainfall (%)	Summer	-34.2	-15.9	+1.9	-48.2	-22.9	+1.7
	Spring	-14.9	-4.7	+5.8	-17.4	-6.2	+5.3
	Winter	-5.8	+7.0	+20.3	-4.6	+11.5	+30.1
Temperature (°C)	Summer	+0.6	+1.6	+2.7	+1.2	+2.6	+4.1
	Winter	0.0	+0.9	+1.9	+0.5	+1.7	+3.0

Acknowledgement

The development of this RWH tool was funded via a grant provided by Kent County Council (KCC) through the EU Interreg H2O Star2Seas Project. The authors of the tool are grateful to KCC staff (Tom Henderson and Alan Turner) for their project guidance and support, to the farmers who kindly agreed to participate as case studies for testing and application of the RWH tool including Milush Petrov (DPS Ltd), Tim Chambers (W.B. Chambers Farms Ltd), John and Alex Myatt (Myatts of Mockbeggar) and Tim Place (Place UK) and to Samantha Hughes at the South East Rivers Trust for her valuable support in engaging the project with key stakeholders.

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Annex 1 Description of key variables

Variable	User-defined / default (description)
Farm location (first part of postcode) and postcode district	The user is required to input the first part of their postcode or select the postcode from the drop-down list in order to link their location to the nearest grid point in the climatology dataset. In the tool, postcodes for Kent and the postcode district to which they are associated are embedded in the model. When a user defines the first part of their postcode or select the postcode from the drop-down list, this is automatically linked to the postcode district from which the grid-cell closest to the centroid of the postcode district is assigned. The postcode data were collated from Web platform (https://www.doogal.co.uk/). The postcode data are linked to the historical daily climate (rainfall and reference evapotranspiration, ET_o) data which was previously downloaded from the Climate, Hydrology and Ecology research Support System (CHESS) (1986-2015) Explorer (https://eip.ceh.ac.uk/chess). The X and Y coordinates for each postcode district centroid were found through the website https://gridreferencefinder.com/
Total polytunnel area (ha)	The user is required to input the total area (ha) of polytunnel/s they want the RWH model to consider. The typical specifications of polytunnel size ranges from 50-100 m (length) and 6-10 m (wide). The data for typical polytunnel specifications were derived from Else (2019) and from actual data provided from the case study farmer interviews. The RWH tool requires the total polytunnel area (ha) to calculate the volume of rainwater runoff collected from the polytunnel roof. NB 1 ha = 10,000 m^2.
Crop type	The RWH tool needs information on crop types grown in the polytunnel to estimate crop water requirements, irrigation demand and leaching requirements for the substrate growing media. The RWH tool is currently configured for strawberries (June and ever bearer) and raspberries. The tool can only simulate one crop type at a time so for assessing multiple crop types and areas, the model will need to be run for each crop type and polytunnel area sequentially and then the results combined. Crop water requirements are calculated based on crop evapotranspiration (ET_c). The methodology used was proposed by FAO (Allen et al. 1998). This method uses the reference evapotranspiration (ET_o) downloaded from CHESS explorer website and a crop coefficient (K_c), which is dependent on the crop and cultivar type, local conditions, and crop management, among other factors. The crop coefficient (K_c) assumes three key crop growth stages (initial, mid, and final) with K_c values interpolated between each growth stage to

	represent a smooth growth development. In the RWH tool, K_c values for June bearing (JB) and ever bearer (EB) strawberries were derived from FAO 55 and 56 (Allen et al. 1998). For raspberries data from http://irrigationtoolbox.com/ReferenceDocuments/Extension/BCExtension/577100-5.pdf was used. K_c values for blackcurrants were not available.
Typical start and end dates of irrigation	The timing of irrigation demand for protected soft fruit depends on when the crop is planted, the rate at which it develops in response to climate factors (ET) and the date of harvest. The start and end dates of irrigation for strawberry (JB and EB) and raspberry crops were based on Else (2019) and from data provided by the case study interviews with selected soft fruit growers. The planting date for each crop type can be modified by the end user based on their local cropping information.
Irrigation leaching fraction (%)	Most soft fruit crops under polytunnels are now grown in soilless substrate media (British Summer Fruits, 2017). These require additional irrigation for leaching to prevent the accumulation of salts in the root zone. The recommended additional amount of irrigation applied for leaching over a cropping season is between 10-20%. These values were derived from the interviews with the case study growers and from literature (British Summer Fruits, 2017 and Else, 2019).
Typical dates when polytunnel covers are fitted and removed	Rainwater can only be collected from the polytunnels when the skins or covers have been installed. The dates from when these coverings are fitted and then removed later in the season are important for calculating the period over which rainfall is collected. Published evidence (Else, 2019) and discussions with key informants and the case study farmers confirmed that the start months for installing polytunnel covers for all protected cropping ranges between Feb and April. The timing for polytunnel cover removal varies based on crop maturity. For example, for June bearer and ever bearer strawberries the polytunnel coverings are removed around July and October, respectively.
Minimum and maximum storage capacity to be evaluated	The RWH tool requires the user to define a minimum and maximum storage capacity (m^3). The capacity is an important component of RWH systems as it determines the proportion of rainwater that can be usefully collected from the polytunnels and the amount that can be provided to meet irrigation demand There is a trade-off between storage capacity and irrigation demand. A storage tank that is too small will mean only a small proportion of rainwater can be collected and not all the irrigation demand will be satisfied (leading to a high irrigation deficit); conversely, a large reservoir or tank will capture most (or all) of the rainwater runoff and meet all the irrigation demand but will be very expensive. The RWH tool therefore provides an option to investigate different reservoir sizes.

Alternative water source and their cost	Four alternative sources of irrigation water (mains, surface water abstraction, reservoir (lined) and reservoir (unlined) are included in the RWH tool. The costs for each source were gathered from literature (Else, 2019; Environment Agency, and Weatherhead et al., 2014) and are inflated to 2020 price.
Proportion of polytunnel area that is cropped (%)	The RWH tool assumes the cropped area to be the same as the polytunnel roof area (100%). The user can modify based on experience.
Polytunnel runoff efficiency (%)	This parameter is used to calculate the potential volume of rainwater that can be usefully collected from the polytunnel area. This is a function of reliable local rainfall and system configuration, as well as factors influencing runoff such as the polytunnel structure and size, slope. The runoff efficiency is also influenced by initial depressional storage losses and losses due to wind effects around the polytunnel, evaporation and other losses through the collection (gutter or membrane) systems. Considering all these factors a value of 85% was originally defined by the Environment Agency (2009), however, this was revised and increased to 95% by Else (2019) for *in situ* cropping system using gutters in a research setting. However, the runoff efficiency can be as low as 50% for membrane based rain-water collection system derived from farmer's interview. In this study, a default value of 90% was chosen.
Rainfall threshold: minimum amount before runoff occurs (mm)	Not all rainfall that lands on a polytunnel can be collected, as it will depend on the length, intensity and amount of rainfall. Very small rainfall amounts will not result in any runoff after accounting for depressional storage, wind drift, evaporation. In this study, it was therefore assumed all rainfall events greater than 2mm will be usefully collected by the RWH system.
Polytunnel evapo-transpiration as % of outdoor evapo-transpiration	Crops grown under plastic are subject to different levels of evapotranspiration (ET) compared to crops grown outdoors. The plastic covers impact on the transmissivity of the incoming solar radiation. The polytunnel structures also modify the ambient environmental conditions with reduced windspeeds and raised humidity levels. It is therefore important to modify (usually lower) the external reference evapotranspiration (ET_o) values to represent the conditions inside the polytunnel. Daily time series gridded reference evapotranspiration (ET_o) data were extracted from the Climate, Hydrology and Ecology research Support System (CHESS) climatology (Robinson et al., 2017). Although an adjustment factor of 50% was derived from Garcia-Tejera et al. (2018) for Spanish polytunnels, this factor was adjusted up to (70%) to match the irrigation need for JB and EB strawberries demonstrated by Else (2019).

Required emergency reservoir storage (hours)	Polytunnel cropping systems are highly vulnerable to any disruption in water supply for irrigation. It is therefore prudent for RWH systems to incorporate some temporary short-term storage capacity to buffer against a supply failure. For a given storage capacity, the RWH model therefore calculates 2 days (48 hr) storage based on peak irrigation demand. This value was derived from interviews with irrigation consultants and suppliers to not allow the reservoir storage to go below 2 days of peak gross water demand.

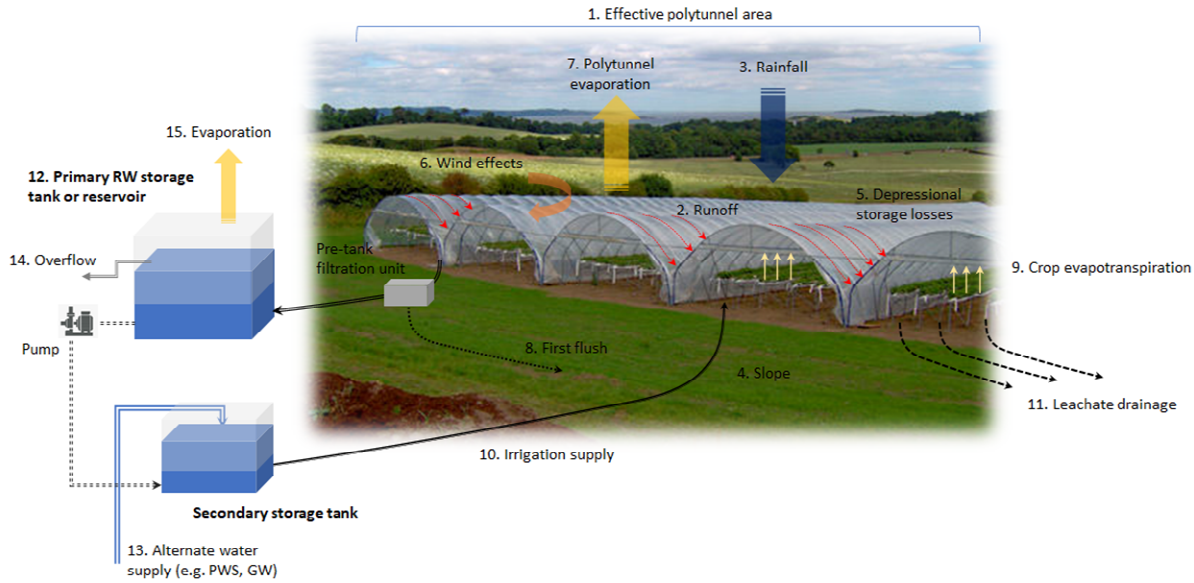
Annex 2 RWH tool description

The high-level conceptual framework for the RWH model is shown in Figure A1 below. This has been developed from published evidence on RWH systems (Environment Agency, 2009) but also incorporating our own understanding of the RWH and soft fruit production systems.

For a given site and polytunnel area, the potential daily volume of runoff or harvested rainwater, is a function of reliable local rainfall and system configuration, as well as factors influencing runoff such as polytunnel structure and size, slope and whether coverings are permanent or seasonal as these influence harvested rainfall volumes as well as irrigation demand. Runoff collection is influenced by initial depressional storage losses and losses due to wind effects around the polytunnel, and evaporation.

Irrigation needs for soft fruit are dependent on the specific crop evapotranspiration rates (ET_c) for strawberries (June bearer and ever bearer) and raspberries and the cropped area. This will impact on irrigation supply and leaching drainage losses necessary to maintain tabletop systems. The daily balance between water inputs into the RW storage tanks (from runoff collected and any alternative water supply from public water supply or private boreholes) and outputs (irrigation supply to the crop, overflows from storage tanks), taking account of the available storage volume determines supply reliability.

Figure A1. Conceptual framework for modelling RWH system for horticultural polytunnel cropping.



Annex 3 RWH tool decision rules

A set of decision rules were defined in terms of modelling inputs and outputs with algorithms then developed for three main modules, (i) irrigation water demand, (ii) polytunnel hydrology, and (iii) RWH economics. At the core of the RWH tool is a daily time-step water balance model which uses various input datasets (pre-determined and embedded and user-defined) and a set of algorithms and coefficients to calculate the components of the polytunnel water balance (effective rainfall, crop evapotranspiration; interception, potential runoff, irrigation demand, storage volume).

30 years (1986-2015) of daily historical weather data from the CHESS (Climate, Hydrological and Ecological research Support System) website have been used. CHESS is a 1 km^2 resolution gridded climatology with continuous daily rainfall from CEH GEAR (Gridded Estimates of daily Areal Rainfall) for the UK and evapotranspiration data. We have extracted data for the grid-cell closest to the centroid of each postcode district in Kent, enabling the tool to use locally derived climate data for each users' locality.

The RWH model was developed using the runoff and water balance model to assess how reliably gross irrigation demand (m^3) could be met using rainwater harvested from the defined polytunnel area for a given location. The tool was developed in Microsoft Excel, with data input through a user-friendly interface and all embedded algorithms password protected for security. A set of decision rules provide operational constraints for the model. For a given site and polytunnel area, the tool estimates the potential daily volume of harvested rainwater, taking into account system type, as well as factors influencing runoff such as slope and whether polytunnel coverings are permanent or seasonal as these influence harvested rainfall volumes. The model incorporates runoff coefficients to cater for initial storage losses and a constant proportional loss to account for wind effects around the polytunnel and evaporation. Model parameterisation are informed by the peer-reviewed literature on polytunnel RWH and through engagement with key informant growers from Kent.

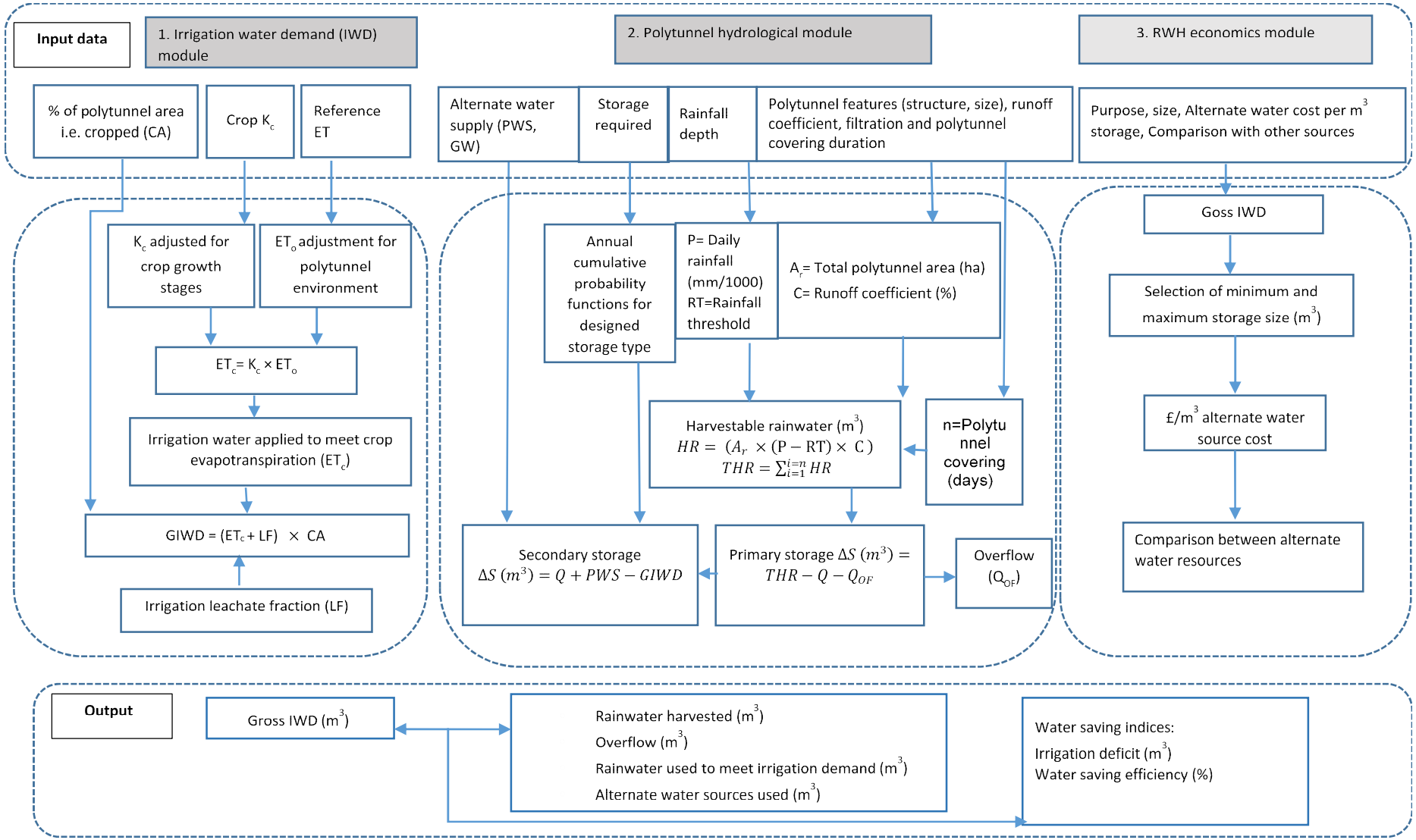
The detailed decision rules for modelling the RWH system for horticultural crops are provided in Figure A2. The key modules and their decision rules considered for modelling RWH system are (i) Irrigation water demand module. (ii) Polytunnel hydrological module and (iii) RWH economics module. In the irrigation water demand module, the crop type, effective cropping area, crop coefficients, and the reference evapotranspiration (ET_o) from gridded CHESS data for each postcode district will be used as inputs. The irrigation needs (depths applied, mm) for strawberries, raspberries and blackcurrants are modelled using existing relationships between ET_o (adjusted to polytunnel system) and the crop coefficients, from published data and through discussions with selected farmer contacts. Irrigation leaching fraction is specified by the user.

The polytunnel hydrological module includes the polytunnel features (effective runoff area, runoff coefficient, rainfall threshold) and duration of covering of temporary polytunnels (days), rainfall depth (mm) from gridded CHESS data for each postcode district, expected storage volume (m^3) and the irrigation water (m^3) required from alternative supply. Using daily time-step simulations of rainwater volume harvested, irrigation need and available stored water, the model estimates the supply reliability for both an average, 'design' very dry year (10% exceedance for irrigation demand)

and driest year to calculate the relative net benefits of different polytunnel areas and required reservoir storage volumes to irrigated area ratios. We have also included simple functionality for end-users to adjust rainfall and ET input values based on the UKCP18 climate change projections to investigate how future changes in climate might impact on harvested rainwater volumes.

The inputs for RWH economics include the water costs (£ per m^3) from alternative sources. This will provide users with necessary information for choosing a suitable RWH system for polytunnel based horticultural cropping.

Figure A2: Decision rules for modelling the RWH system for polytunnel soft fruit crops.



Notes: ET_o; Reference evapotranspiration, ET_c; Crop evapotranspiration, K_c; Crop coefficient, PWS; Public water supply, GW; Ground wells, P; Daily rainfall, ΔS; Reservoir water storage, HR; Daily harvested rainwater, THR; Inflow of total harvestable rainwater to primary storage, Q; Outflow from primary storage to secondary storage, Q_{OF}; Overflow from primary storage

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