

ROBUST RAINWATER HARVESTING: PROBABILISTIC TANK SIZING FOR CLIMATE CHANGE ADAPTATION

Short Title: Probabilistic RWH tank sizing for climate change adaptation

Daniel Lash^a, Sarah Ward^b, Tristan Kershaw^c, David Butler^b, Matthew Eames^a

^a Centre for Energy and the Environment, University of Exeter, Rennes Drive, Exeter, EX4 4RN, UK

^b Centre for Water Systems, University of Exeter, North Park Road, Exeter, EX4 4QF, UK

^c Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, UK

Lead author contact details: d.lash@ex.ac.uk

ABSTRACT

Rainwater harvesting (RWH) systems are increasingly being implemented in buildings. It is common in the UK for simple RWH tank sizing methods to be utilised, and these do not consider future climate change. This paper describes the development of a tool, which integrates elements of basic and detailed sizing approaches from the British Standard for RWH, with the latest probabilistic UK Climate Projections data. The method was initially applied to the design of a university building in Cornwall, UK. The methodology utilises 3000 equi-probable rainfall patterns for tank sizing for each time period. Results indicate that, to ensure that it is ‘likely’ that the same non-potable demand could be met in 2080 as in the present, a tank 112% larger would be required. This increases to a 225% over-sizing

for a ‘very likely’ probability of meeting the same level of non-potable demand. The same RWH system design was then assessed for three further UK locations with different rainfall characteristics. From these assessments a simplified method was developed to enable practitioners to size RWH system tanks for current and future climates. The method provides a new approach to meet present and future non-potable demands, while preventing excessive over-sizing of tanks.

Key words | adaptation, climate change, probabilistic, rainwater harvesting, resilient, tank sizing

ABBREVIATIONS AND NOTATIONS

<i>A</i>	Collecting area (m ²)
BREEAM	Building Research Establishment Environmental Assessment Method
CV	Coefficient of variation
<i>D_s</i>	Maximum potential annual demand satisfied
<i>D_N</i>	Annual non-potable water demand (litres)
<i>e</i>	Yield coefficient
ESI	Environment and Sustainability Institute
<i>h</i>	Annual rainfall for the site location (mm)
IPCC	Intergovernmental Panel on Climate Change
<i>n</i>	Number of persons
<i>P_d</i>	Daily requirement per person (litres)
<i>P_{current}</i>	Annual percentage of non-potable water demand met by the RWH system collecting 50% of rainfall for the defined period of collection under the current climate

P_{future}	Percentage of non-potable water demand met based on the tank sized for the future climate
PTST	Probabilistic tank-sizing tool
RWH	Rainwater harvesting
UKCP09	UK Climate Projections 2009
Y_{MAX}	Theoretical maximum rainwater collection
Y_R	Annual rainwater yield (litres)
YAS	Yield after spillage
YBS	Yield before spillage
η	Hydraulic filter efficiency

INTRODUCTION

Throughout the world, water resource issues are receiving heightened attention, under the scope of various campaigns such as ‘Making Poverty History’, the United Nation’s Millennium Development Goals (Ashley *et al.* 2008) and the European Commission Consultation on Policy Options for the Blueprint to Safeguard Europe’s Waters (European Commission [EC] 2012). In the UK, the ‘Securing the Future’ sustainable development strategy (Defra 2005) acknowledged that one of the most significant pressures on the global environment is through water consumption. For water management in the UK, this was further recognised by the ‘Water for Life’ Water White Paper released (Defra 2011). ‘Water for Life’ highlights that water reuse should form an important part of water management strategies, as evidenced by the following paragraph:

'When all steps to minimise existing water use have been taken, we should consider collecting and reusing rainwater and recycling grey water, particularly in new buildings or those undergoing major renovation. Reusing water can reduce pressure on the supply system and our drainage infrastructure.' (2.2, page 20).

Rainwater harvesting (RWH) systems are increasingly being implemented to supply end use demands that do not require potable quality water, for example toilet flushing and irrigation. For such non-potable end uses, RWH can supplement mains water supplies, to reduce potable water consumption within the built environment (Ming-Daw *et al.* 2009). This should help reduce water stress in areas suffering from water resource issues. Utilisation of RWH systems could become increasingly important under scenarios of rising population and climate change, as potable water resources are put under pressure and as the cost of water may increase (Defra 2011).

A range of international approaches to incorporate RWH systems (and other 'alternative' water systems) into the built environment exist and include: the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK (BREEAM 2011); Best Management Practices (BMPs) or Low Impact Development (LID) in the USA (DER 1999); Low Impact Urban Design and Development (LIUDD) in New Zealand (Van Roon *et al.* 2006) and Water Sensitive Urban Design (WSUD) in Australia (Coombes *et al.* 1999; Howe & Mitchell 2012).

Within these approaches, a number of different RWH system tank sizing methodologies are utilised (UK methods are described in depth in the following section). In order for a RWH system to be adapted to climate change, it is argued that

it should be able to perform at the same level under the future climate, as it does when sized to meet the current climate (Youn *et al.* 2012). This paper presents a methodology to achieve this by the development and application of a probabilistic approach. The second section of the paper describes the relevant theory behind RWH system tank sizing. The third section describes the development of the probabilistic modelling approach and the case study to which it is applied. The fourth section describes the results from applying the model to the case study. The paper finishes by discussing the implications of the results and drawing conclusions.

Rainwater harvesting tank sizing theory

A number of methods and models have been developed for sizing RWH systems, such as the Rewaput model (Vaes & Berlamont 2001), the Rainfall-Storage-Runoff (RSR) model (Kim & Han 2006) and the RainCycle© model (Roebuck *et al.* 2011). A more detailed summary of such models is provided in Ward *et al.* (2010). More recent models are continuous simulations based on research on yield-before and yield-after spillage algorithms (termed YBS and YAS, respectively) developed by Fewkes (1999) and Fewkes and Butler (2000). The YAS and YBS rules determine the timing of supply, demand and overflow in the calculation of storage volume. From this research it was concluded that the YAS operating rule (with an hourly or daily rainfall time series) provided the most accurate, conservative results. Such methods and models have been applied to evaluate RWH schemes in many parts of the world (Ward *et al.* 2012)

Building on this research and work undertaken in Germany to produce a RWH system standard (DIN 1989), a British Standard (BS 8515:2009) for RWH systems was

produced in 2009 (British Standards Institution [BSI] 2009). BS 8515 recommends three methods for sizing RWH storage tanks, depending on the type of building under consideration and the availability of data, such as rainfall, building occupancy rates and roof areas. The three methods are the Simple, the Intermediate and the Detailed Approaches. The Simple Approach uses simple look-up charts, which relate average rainfall bands for the UK to building roof areas and occupancy rates for domestic buildings. The Intermediate Approach goes a step further and uses Equations (1) and (2) to estimate the tank size. Equation (1) calculates 5% of the annual rainwater yield and Equation (2) calculates 5% of the annual non-potable water demand.

$$Y_R = A \cdot e \cdot h \cdot \eta \cdot 0.05 \quad (1)$$

Where:

Y_R is the annual rainwater yield (l);

A is the collecting area (m²);

e is the yield coefficient (%);

h is the annual rainfall for the site location (mm);

η is the hydraulic filter efficiency.

$$D_N = P_d \cdot n \cdot 365 \cdot 0.05 \quad (2)$$

Where:

D_N is the annual non-potable water demand (l);

P_d is the daily requirement per person (l);

n is the number of people.

The storage capacity should be estimated from the lesser of the two of these calculations, which represents approximately 18 days of storage (i.e. 18 divided by 365 is approximately 5% of the year). BREEAM utilises the Intermediate Approach when recommending the inclusion of RWH systems though requires the tank to be sized at 50% of the output of the Intermediate Approach. Therefore, to meet the BREEAM credit requirement a RWH tank is effectively sized using the BS 8515 Intermediate Approach with approximately 9 days of storage. However, Neumann *et al.* (2011) demonstrated that the use of such average approaches can lead to overestimated yields and volumetric reliability, as well as underestimation of overflow and nutrient export, when used to linearly up-scale performance from a single RWH system to a cluster of RWH systems.

The Detailed Approach to sizing storage capacity recommends the development of a model of yield and demand that should be based on a continuous daily rainfall time series for a minimum of 3 years and preferably 5 years. It recommends use of such a model where:

- a) Demand is irregular (e.g. external use, non-domestic use, tourism);
- b) Yield is uncertain (e.g. due to the use of green roofs, permeable pavements);
- c) Costly, very large or complex RWH systems are proposed.

However, the standard does not suggest the types of assumptions that should be used to characterise irregular demand and it does not make recommendations to utilise a particular model or piece of software.

The previously described models implement variations of the Detailed Approach. However, they do not necessarily implement a probabilistic rainfall approach, which is required to assess the potential adaptability and resilience of RWH tank sizes generated under climate change scenarios. Research in this area is growing, as exemplified by studies undertaken by Ming-Daw *et al.* (2009) and Youn *et al.* (2012). The latter study downscaled a scenario from the Canadian Global Coupled Model 3 using the Statistical Down Scaling model and applied it to a case study University building RWH system. A set of curves describing the relationship between storage capacity and deficit rate (the ratio of total deficit volume to total demand) was derived. From these curves, it was determined that under the Intergovernmental Panel on Climate Change (IPCC) A2 emissions scenario, the RWH system tank volume could be reduced due to increased annual mean precipitation. This is an interesting finding as it implies that tanks sized for the current climate would be pre-adapted to climate change. However, it should be noted that rainfall patterns for the UK are likely to be different to the case study location (S. Korea), also the IPCC A2 scenario is more conservative than the IPCC A1FI scenario used for this study. While annual rainfall in the UK is not predicted to change by more than a few per cent the distribution of rainfall is. It is projected that there will be significantly more rainfall in winter and a reduction in summer. The intensity of rainfall events is also expected to increase. These factors imply that a RWH system sized for the current UK climate could be poorly adapted for future climates. The following section describes the

development and application of a model based on the approaches recommended in BS 8515, but that includes a probabilistic rainfall approach to assessing RWH system tank sizing for the UK using projected future climate data.

METHODS

The methodological approach undertaken within this paper consists of three distinct parts. The first part is the development of a probabilistic tank-sizing tool (PTST) based on the theoretical principles described in the Introduction section. The second part is the detailed application of the PTST to a case study RWH system design within a large building in the UK for various climate scenarios. The third and final part is the inclusion of rainfall data for different UK locations within the application of the PTST to the same large building design. **Error! Reference source not found.** summarises the main components of the methodology. In this methodology it has been assumed that the RWH tank size is based on the roof supply as typically used in practice. However, this may not always be the case and the method could equally be applied to any other supply.

The probabilistic tank-sizing tool (PTST)

The probabilistic tank-sizing tool consists of two main components. The first component is a RWH tank-sizing tool, which implements a number of underlying algorithms based on the theoretical principles outlined in the Introduction section. The second component is the coupling of the tool with UK Climate Projections 2009 (UKCP09; Defra 2009) Weather Generator datasets. These are described below.

PTST – Underlying algorithms

Using Equations (1) and (2) and data summarised in Table 1, a storage tank volume was calculated for the case study building, representing the minimum required to meet the BREEAM requirement of 50% of annual rainwater yield during the defined period of collection (Equation (1)) to be collected. This volume was used as a baseline tank size for the PTST assessments. The PTST combines this element of the Intermediate Approach with application of the Detailed Approach and a YAS algorithm by means of an iterative model to calculate daily potential rainwater yield, non-potable water demand and an upper limit for the tank size.

The PTST assumes that any roof run-off collected whilst the tank is full is discharged to the local drainage system. Any shortfall in the supply of harvested rainwater is assumed to be met by the mains water supply. From this model for the case study building, the annual percentage of non-potable water demand met by the RWH system sized using the BREEAM criterion to collect 50% of rainfall for the defined period of collection could be established. This value was termed $P_{current}$. The baseline tank size was used to calculate $P_{current}$ using the 100 samples of 30 years of control daily rainfall data for the site output by the UKCP09 Weather Generator, representative of the period 1961-1990 (Jones *et al.* 2009). Within the PTST, the volume in the tank each day is then updated using the available rainfall and the required demand to find the cumulative non-potable demand met.

In order to examine the impact of future climate scenarios on tank sizing and performance (in terms of % of demand met), the PTST was applied using UKCP09 probabilistic climate change projections. Specific site rainfall was obtained using the Weather Generator which is a downscaling tool that can be used to generate

statistically plausible daily and hourly time series. These time series comprise a set of climate variables at a 5 km resolution that are consistent with the underlying 25 km resolution climate projections. Calculations were performed for the 2030s, 2050s and 2080s under the High emissions (A1FI) climate change scenario (described in the next sub-section). Each set of data represents a 30-year rolling time period. The UKCP09 Weather Generator allows weather and climate data specific to the location of the case study building to be created. The percentage of non-potable water demand met based on the tank sized for the future climate could therefore be calculated and was termed P_{future} , with the term ‘future’ representing the time horizon under consideration. In this case the three future scenarios examined were P_{2030} , P_{2050} and P_{2080} , respectively.

PTST and future climate scenarios – Using UKCP09 Weather Generator

datasets

Currently there is uncertainty in the extent to which climate change will affect the built environment (IPCC 2007). This is due to a number of reasons, including the climate model, natural climate variability and future greenhouse gas (GHG) emissions (Murphy *et al.* 2009). For the UK, these uncertainties are represented by the climate change projections produced by the Department for Environment, Food and Rural Affairs’ UK Climate Projections 2009 (UKCP09) project (Defra 2009).

GHG emissions uncertainty is handled in UKCP09 by the production of climate change projections for three emissions scenarios: Low (B1), Medium (A1B) and High (A1FI). However, current research has demonstrated that current emission trends imply that actual future emissions could be far greater than that assumed by the A1FI scenario (Anderson *et al.* 2008). As a result, the effects of climate change could be

more detrimental than those predicted by the A1FI scenario. In this paper only the A1FI emissions scenario will be considered, as it covers a more extreme range of climate change impacts and gives an upper bound to the climate change adaptation strategy for the most current projections. However, the methodology presented here could be used with another emissions scenario if desired.

Within UKCP09, probabilistic climate change projections have been made available where percentiles represent the fraction of the models, which produce a level of climate change at least as large (Murphy *et al.* 2009). These are produced by the UKCP09 Weather Generator (Jones *et al.* 2009). In this paper 100 equi-probable independent sets of 30 years of daily rainfall data were used for each of the three time horizons, resulting in the total consideration of 3,000 probabilistic rainfall patterns. UKCP09 uses calibrated uncertainty language to convey the probabilistic nature of the data, typically defined as: 10th percentile – very unlikely to be less than, 33rd percentile – unlikely to be less than, 66th percentile – unlikely to be greater than and 90th percentile – very unlikely to be greater than. The 50th percentile is the central estimate and is equally likely as not.

Case study building and RWH system

The case study building used in this study is the University of Exeter's Environment and Sustainability Institute (ESI). It is a research institute to facilitate teaching, research and commercial application of environmental and sustainability knowledge. The ESI building is located in Penryn, Cornwall, UK and will combine a series of academic, laboratory and office accommodation. The building has been designed to achieve a rating of 'Outstanding' under the bespoke version of BREEAM (2011).

BREEAM Outstanding represents the highest sustainability standard of the time. A further ambition of the project is to ensure the building is adaptable to the impacts of climate change. An element of the sustainability strategy includes water conservation and the building has been designed with a RWH system to meet the BREEAM criteria.

Harvested rainwater supply and demand parameters

As per Equations (1) and (2), certain rainwater supply and demand parameter values are required to estimate RWH tank sizes. For the ESI building, these are summarised in Table 1. The most common non-potable water-using applications that RWH is currently used for are flushing toilets and irrigation. The ESI is a 3-storey building with a net floor area of 2925 m² (gross internal floor area of 3429 m²). To estimate the non-potable demand for the building, it was assumed that the average occupancy would be 300 and that occupants would be present in the building for every day of the year. In practice there would be weekly and seasonal variations. For example, it is likely that during the University summer vacation, the occupancy and demand for water would be lower, as staff and students frequent the building less regularly. It is therefore recognised that the assumption of year-round occupancy of 300 has its limitations. It was also assumed that there was an equal split of men and women in the building. In terms of outdoor potential for non-potable water use, there is no irrigation to the landscaping on the site and therefore this requirement was not included in the calculations.

Table 1 Supply-demand parameters and values used in this paper.

Parameter - Supply	Value	Parameter - Demand	Value
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Design rainfall value (mm)	1213	Floor area (m ² , gross internal)	3429
Roof catchment area (m ²)	1050	Floor area (m ² , net)	2925
Run-off coefficient	0.5 (flat roof)*	Occupants (number)	300
Filter coefficient	0.9*	Occupancy (days per year)	365
		Effective flush 6/4 WC (l)*	4.5
		Effective flush urinal (l)*	1.5
		Toilet use per day per person*	1.3
		Urinal use per day per male occupant*	2

* From BREEAM guidance

Penryn represents a wet climate relative to the most populated parts of the UK (Met Office 2012). For the ESI, it can be stated that it is ‘very unlikely’ that by the 2080s mean total annual rainfall will decrease or increase by more than 10% (Murphy *et al.* 2009). However, this headline statistic masks likely changes in *seasonal* distribution of rainfall. Average estimates for the 2080s (2070 to 2099) for the site indicate that whilst winter precipitation may increase, summer rainfall could fall by 30 to 40% (Defra 2009). Clearly, this has potentially significant impacts on the sizing of RWH tanks and the non-potable demand satisfied by RWH, if the building is to be considered to be adaptable for changes in climate.

Using the parameter values and by applying the PTST outlined in this section, the tank size and water saving performance of the RWH system was assessed under future climate scenarios, in order to understand the potential adaptability of the ESI RWH system.

Application of the probabilistic tank-sizing tool

To achieve the BREEAM requirement a RWH storage tank is normally sized to collect at least 50% of either predicted rainwater yield or total flushing demand (whichever is the lesser) over a defined period of collection (usually 18 days), as highlighted in Equations (1) and (2). Using the parameter values outlined in Table 1, the design team for the ESI had estimated the daily non-potable water demand to be 2205 litres, or 804,825 litres for one year (365 days). Consequently, they sized the tank to collect 50% of the predicted rainwater run-off for the building, based on its roof area and the average annual rainfall for the site (Table 1), by applying the Intermediate Approach. This resulted in a baseline tank size of 14,138 litres. Clearly in practice, tanks are available commercially in discrete sizes and so, for example, in this case a 15,000 litre tank might be specified.

In order to meet the aim of ensuring a tank is sized to be adapted to future climate conditions by attaining the same level of performance under climate change as under the current climate, the relationship between current and future performance can be described as $P_{current} = P_{future}$. Calculations were performed with the required outcome for each rainfall series being to size the tank such that P_{future} was maintained at $P_{current}$. An iterative procedure was established in the PTST, whereby the tank size was incrementally altered until P_{future} converged at $P_{current}$ or until the addition to the size

of the tank made less than 0.01% difference to the non-potable demand met. For each time horizon (2030s, 2050s and 2080s) this process returned a range of tank sizes that was dependant on the specific rainfall volume and pattern for each climate change sample. In order to test the PTST, it was applied to the ESI RWH system tank sizing design, using the baseline tank size of 14,138 litres.

To test the PTST under a range of different spatial rainfall scenarios and to assess its applicability to other projects, it was applied to the ESI building as if it were located in other parts of the UK. This could also be undertaken for sites in other countries where projections of daily rainfall under future climate scenarios are available. Calculations were performed to investigate additional parameters, such as the theoretical maximum rainwater collection for each geographic location. This was calculated using Equation (3).

$$Y_{MAX} = h \times A \times e \times \eta \quad (3)$$

Where:

Y_{MAX} is the theoretical maximum rainwater collection

h is the annual rainfall for the site location (mm)

e is the yield coefficient (%);

η is the hydraulic filter efficiency.

The ratio of Y_{MAX} to the annual demand, representing the maximum potential annual demand satisfied, was termed D_S . The total annual demand was then varied to give a

range of demands within a range for D_S of 10% to 100%. It was assumed that the daily demand was constant, therefore the annual demand was divided by 365 to obtain the daily demand. The PTST uses a single value for daily demand for water that comprises the cumulative demand for non-potable water from all uses within the building. For example, a daily demand of 1000 litres could arise from 100 litres of toilet flushing and 900 litres of irrigation, or from 500 litres of each of these. The outcome would be the same within the PTST. This allows for a high level of flexibility in the approach. This was used in the calculations to establish $P_{current}$ and P_{future} using the method described above for each variation of D_S . If desired further complexity could be added by incorporating variable demand into the calculation but this was deemed unnecessary for this study.

These calculations were performed for the ESI at Penryn and then for the following UK locations: Cambridge (Cambridgeshire), Aberdeen (Aberdeenshire) and Ammanford (Carmarthenshire). These were chosen as being representative of a range of rainfall volumes and patterns across the UK. The daily demands required for each of these additional sites for each value of D_S are shown in Table 2. In reality the actual annual demand satisfied is usually lower than the maximum potential D_S due to the timing of supply, demand and overflow resulting from variation in weather.

Table 2 Daily demand (litres) for the ESI building for four sites in the UK ('as designed' annual demand satisfied values shown as a percentage in parentheses).

	Penryn	Cambridge	Aberdeen	Ammanford
D_S	(71.2%)	(32.6%)	(44.7%)	(86.1%)

10%	15,708	7197	9853	18,987
25%	6283	2879	3941	7595
50%	3142	1439	1971	3797
75%	2094	960	1314	2532
100%	1571	720	985	1899

RESULTS AND DISCUSSION

Values calculated for $P_{current}$ ranged from 59.8% to 64.4% with a mean value of 61.9% with a standard deviation of 0.95% and a coefficient of variation (CV) of 0.015. The median value of $P_{current}$ was 61.8%. The median value was taken to describe the current performance of the rainwater harvesting system based on the BREEAM/BS 8515 Intermediate Approach requirement to size the tank based on collecting 50% of annual rainfall. The ratio of the maximum theoretical supply to the annual demand (D_s) was calculated as 71.2%.

Meeting demand under future climate scenarios

For the ESI RWH tank sized to hold 50% of rainfall as per BREEAM requirements, the median value of $P_{current}$ was 61.8%. Under future climate it is likely that for the same size tank, a lower proportion of annual demand will be met by the RWH system. The reduction will depend on the magnitude of the climate impact and in some cases the amount of demand met could actually increase. Underground RWH tanks are estimated to have life spans typically around 50 to 60 years (Roebuck *et al.* 2011). A tank installed in the present (2012) could therefore last into the 2080s. Consequently, for a proposal to ensure the building is adapted to climate change ($P_{current} = P_{future}$) the 2080s time horizon was selected. As new projections for climate change become

available then data may be available at finer time resolutions, for example with projected rainfall on an annual basis for the coming century. This would allow the selection of time horizons that directly correlate to whole RWH systems, or components within a system. In the application of the PTST, the selection of the time horizon would be an option that is available to a system designer, and may be influenced by factors such as the most up to date knowledge on system component lifetimes, or attitude to risk. The annual percentage of non-potable water met by the rainwater system to collect 50% of rainfall under the climate in the 2080s was designated P_{2080} .

For the 14,138 litres baseline tank there is an equal probability that the P_{2080} will either be more or less than 57.8%, a likely probability (33rd percentile) that P_{2080} will be greater than 56.8% and a very likely probability (10th percentile) that P_{2080} will be greater than 53.9%, as illustrated in **Error! Reference source not found.** Therefore, relative to the present climate it is unlikely that in the 2080s the demand met from the RWH system will reduce by more than 8.2%, and very unlikely that it will reduce by more than 12.8%.

Tank size required under future climate scenarios

The results for calculations for the tank size required under future climate to ensure $P_{current} = P_{future}$ are shown in **Error! Reference source not found.** Under $P_{current}$ the tank was sized at 14,138 litres. For P_{2080} it is unlikely that the tank will need to be larger than 29,900 litres and very unlikely that it will need to be larger than 46,000 litres. This is 112% and 225% larger in size than the tank sized for the current climate, representing significantly larger increases in capacity in comparison with the potential

reductions of 8.2% or 12.8% in demand met that could occur if the capacity of the tank were not increased. Indeed, the increase in tank size required to improve the probability of success from likely (66th percentile) to very likely (90th percentile) is large, a 56% increase in tank size is required.

Varying collection days to achieve annual demand satisfied (D_S) – ESI

The results of varying the maximum potential annual demand satisfied (D_S) are shown in **Error! Reference source not found.** for ESI. For completeness the 1st and 99th percentile tank sizes are shown, but the robustness of the projections towards the tail of the distribution is reduced. The percentile tank size represents the confidence level for achieving a given D_S . The results are normalised to express the days within the defined period of collection as stated in Equation (3). The value that is used under present climate is 18 days, therefore values greater than this imply a larger tank is required than one that is sized for the current climate, to ensure the same demand is met under future climate. Each series in Figure 4 refers to a percentile tank size. Therefore the values for a D_S of 71% (as designed for Penryn) relate to the values in Figure 3 for the 2080 series prior to their normalisation. As D_S increases, a larger tank size is needed. This increase is dependent on the confidence level required, with proportionally greater tank sizes needed in order to increase the certainty that the tank will be large enough such that $P_{current} = P_{future}$. The percentage probability (confidence level) values were determined by ranking the output tank size for each of the 3000 annual rainfall series under each time horizon. The ordering of the tank sizes is therefore not only strongly influenced by the volume and annual distribution pattern of the rainfall within each year, but also by the relationship between the ratios of supply and demand to the amount of rainfall available. Data points are plotted for

demand satisfied values of 10%, 25%, 50%, 75% and 100%, as well as the ‘as designed’ values, which for Penryn is 71%.

Varying collection days to achieve annual demand satisfied (D_s) – Other locations

The results are shown for Cambridge, Aberdeen and Ammanford as they were for Penryn in Figures 5-7. The observed results up to the 66th percentile probability level are similar to those for the ESI at Penryn. However, at the 90th and 99th percentile probability levels the relationship of increasing tank size with meeting a greater proportion of rainwater does not always hold true. The reason for this is because D_s has been adjusted by maintaining a constant supply and altering demand. Therefore a high value of D_s is due to a lower absolute demand for example for Cambridge and Aberdeen a D_s of 50% corresponds to a demand of 1439 and 1970 litres per day respectively whereas a D_s of 75% corresponds to a demand of 960 and 1314 litres per day respectively. It is therefore possible that a smaller tank could be needed. For the cases of Cambridge and Aberdeen, which are drier locations than Penryn, at the higher percentile probability levels the effect of lower absolute demand for water to achieve a larger D_s results in lower tank sizes. For Cambridge at the 90th percentile a D_s of 50% corresponds to a 21,000 litre tank whereas a D_s of 75% corresponds to a 13,900 litre tank. The effect of lower absolute demand begins to dominate to a greater extent than increasing the tank size, that might be expected, to meet the higher percentage of demand met. In addition the reduced rainfall at Aberdeen and Ammanford, compared to sites such as Penryn, reduces the ability of a tank to meet the shortfall in dry periods.

The D_S varies with location for the ‘as designed’ building which has a non-potable water demand of 2205 litres per day (as shown in Table 1). As Cambridge is the driest site, the value of D_S is only 32.6%, whilst at Ammanford – the wettest site – D_S rises to 86.1%. When these calculations are performed using the future climate scenarios for each of the four sites, we find that the increased tank sizes (as measured by an increase in the number of days in the defined period) increases in a broadly similar manner for each probability level, as is shown by **Error! Reference source not found.** Differences between locations are explained by varying climate change signal magnitude and inherent differences in rainfall volume and pattern across the country, which in turn impacts on the sensitivity of tank sizing due to changes to the climate.

Varying collection days to achieve annual demand satisfied (D_S) for specific confidence intervals – A method

Table 3 shows the change to the number of days in the defined period under projected scenarios for climate change in the 2080s for each of the four sites at the 50th, 66th and 90th percentile confidence levels. There are some instances where the number of days calculated was below 18, which indicates that a smaller tank could be required. For these instances, a value of 18 was maintained as the minimum value, as the tank could not be considered adapted if it achieved the performance level in the future, but not under the current climate. At the 50th percentile probability level, which implies that a tank sized at that level is equally likely to be oversized as undersized, relatively smaller increases in tank size are required to ensure $P_{current} = P_{2080}$.

For Aberdeen, the tank size is found to be relatively constant, regardless of the demand for water from the building. However, whilst at Penryn the tank size remains the same for a large demand from the building (as classified by low value of D_S) and

as demand for water from the building decreases, the tank size increases by up to a factor of approximately two for a D_S of 100%. This is because in order to meet a greater percentage of demand, more water will need to be collected and stored to cover dry spells in the year, for example over a summer. Even though absolute demand for water may be lower, the tank size may still need to be larger to account for the variability in supply. The annual rainfall supplied at Penryn is high enough and the distribution is such that a large tank can be used to satisfy demand during dry periods. The same is not true for drier locations such as Cambridge.

At the higher probability levels (66th and 90th percentile), the required tank sizes increase. As discussed previously, the relationship between percentage of theoretical demand met and tank size becomes more variable as the competing effects of drier climates and increased demand from the building trade-off against one another.

Table 3 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s for the four locations at the 50th, 66th and 90th percentile probability levels.

Location	Probability	D_S				
	(percentile)	10%	25%	50%	75%	100%
	50 th	18.0	18.0	29.3	30.6	36.8
Penryn	66th	18.0	18.0	38.1	39.3	52.2
	90 th	18.0	22.9	58.6	64.9	72.6
Cambridge	50 th	22.2	24.7	24.7	26.4	27.8
	66th	27.8	30.6	30.3	29.5	30.6
	90 th	33.3	44.5	58.4	38.6	36.7

	50 th	18.0	18.0	18.0	18.7	20.5
Aberdeen	66th	18.0	18.0	18.7	20.7	22.4
	90 th	28.4	36.5	36.3	30.2	29.0
	50 th	18.0	18.0	18.0	24.2	29.5
Ammanford	66th	18.0	18.0	20.0	29.4	39.0
	90 th	19.0	23.2	44.2	51.6	71.6

Using the calculated tank sizes under a probabilistic range of climate change weather years, the results produced by the PTST could be used to size rainwater harvesting system tanks in order to meet standards such as BREEAM and ensure that the performance remains resilient to the potential impacts of climate change. The first step would be to calculate the Theoretical Maximum Rainwater Collection as defined in Equation (3). The next step would require calculation of the annual demand for non-potable water, although with the current caveat that daily demand within the year does not vary. These calculations could then be used to calculate D_S and Table 3 used to look-up the adjusted number of days in the defined period of collection. Finally, the adjusted number of days could be substituted into Equation (3) instead of the current 18 days, to calculate the total volume collected. This would then be multiplied by 0.5 to size the tank to meet the requirement to collect at least 50% of predicted rainwater run-off over a defined period of collection.

Limitations of the PTST

A recognised limitation of the PTST, is that it currently only considers meeting the in-building non-potable demand for water. Future work will focus on incorporating an algorithm to include consideration of the RWH system tank's stormwater attenuation

function for large buildings. That is, an algorithm will be added to enable the PTST to consider both the water supply and the surface water management potential of RWH systems under future climate scenarios. The algorithm will be based on the Extended Detailed Approach outlined in BS 8515. This approach recommends that where stormwater control is to be integrated into a RWH, the additional storage capacity needed should be determined in accordance with one of the following methods:

- a) Analysis of 20+ year extreme events;
- b) 100+ year extreme stochastic series;
- c) Probability analysis with a five-year time series.

This will be combined with recent research by (Raimondi & Becciu 2011). To date there has been limited research on the surface water management potential of RWH systems and that which has been undertaken has primarily focused on domestic buildings rather than large, non-domestic buildings (HR Wallingford 2011; Raimondi & Becciu 2011).

A further limitation of the PTST is that it uses aggregated annual demands, rather than trying to model the irregularity of demand that a building such as the ESI would experience. This extra complexity could be included within the model but was omitted for simplicity, making this study easier to replicate. This was in part due to the need to simplify demand to undertake the study described (as there was no information about the building's occupants) and in part due to the lack of detailed datasets or profiles for non-domestic building water demand. This is a frequently recognised issue (Ward *et al.* 2012). Future work will include variance of demand

both within a week or season i.e. occupancy patterns, and between larger time horizons, i.e. technological or societal change.

CONCLUSIONS

A continuous simulation tool (the probabilistic tank-sizing tool, PTST) has been presented that uses an integrated BS 8515: 2009 Intermediate and Detailed Approach, combined with a large sample of probabilistic rainfall data from the UKCP09 Weather Generator, for a series of time horizons (2030s, 2050s, 2080s) for the sizing of RWH system storage tanks. Due to the expected lifetime of both the building and the RWH tank the 2080s (2069-2099) time horizon is perhaps the most relevant to ensure adequate adaptation. The PTST enables estimation of the potential RWH system tank size required for a tank sized under current climate parameters to meet the same level of non-potable demand under projected climate change scenarios. The results indicate that if the impact of climate change scenarios are not considered, the proportion of non-potable water demand met by the RWH system is likely to reduce. However, the reduction is proportionally smaller than the increase in tank size required to off-set the reduction. This is likely due to the changes in rainfall patterns under projections of future climate, which in turn would require increased tank volumes in order to level-out periods of supply and improve water security. This is in contrast to a similar Korean study (Youn *et al.* 2012), which determined that under the A2 climate change scenario using data from a downscaled Canadian Global Coupled Model, RWH system tank volumes could be *reduced* due to increased annual mean precipitation. This highlights the importance of using regionally appropriate climate change scenario weather projection datasets, as climate change projections vary across the globe and will affect local weather patterns in different ways.

Results generated by applying the PTST to a range of sites and demand levels suggests the need to oversize tanks for the current climate in order to provide resilience against projected climate change. A method of undertaking this over-sizing has been presented. The implementation of the method enables a risk-based approach to be taken for any particular RWH system design project. The method deploys an adjusted value for days within the defined period of collection, which is a concept that is already well documented and used by practitioners applying BS 8515 and BREEAM tank sizing methods. The adjusted values for the period of collection have been presented at a range of probability levels. It has been shown that the relationship between demand, supply and future climate follow a similar form up to the 66th percentile probability; that is, at a ‘likely’ level of probability that a tank sized at that volume would meet the same annual demand in the future as in the current climate. At higher probability levels, for example ‘very likely’ that a tank would be sized to meet future climate (90th percentile), the relationship becomes harder to predict between locations and the relative increases in tank sizes are significant. It is therefore suggested that should a universal approach to adapting rainwater tanks for resilience to climate change be adopted, the 66th percentile probability level would provide a balance between a high likelihood of meeting present and future demands, whilst preventing excessive over-sizing of tanks.

ACKNOWLEDGEMENTS

This work was funded through the Technology Strategy Board Design for Future Climate: Design for Future Climate 2 competition and the UK Engineering and

Physical Science Research Council as part of the ReVISIONS consortia (EP/F007566/1) under the Sustainable Urban Environment programme.

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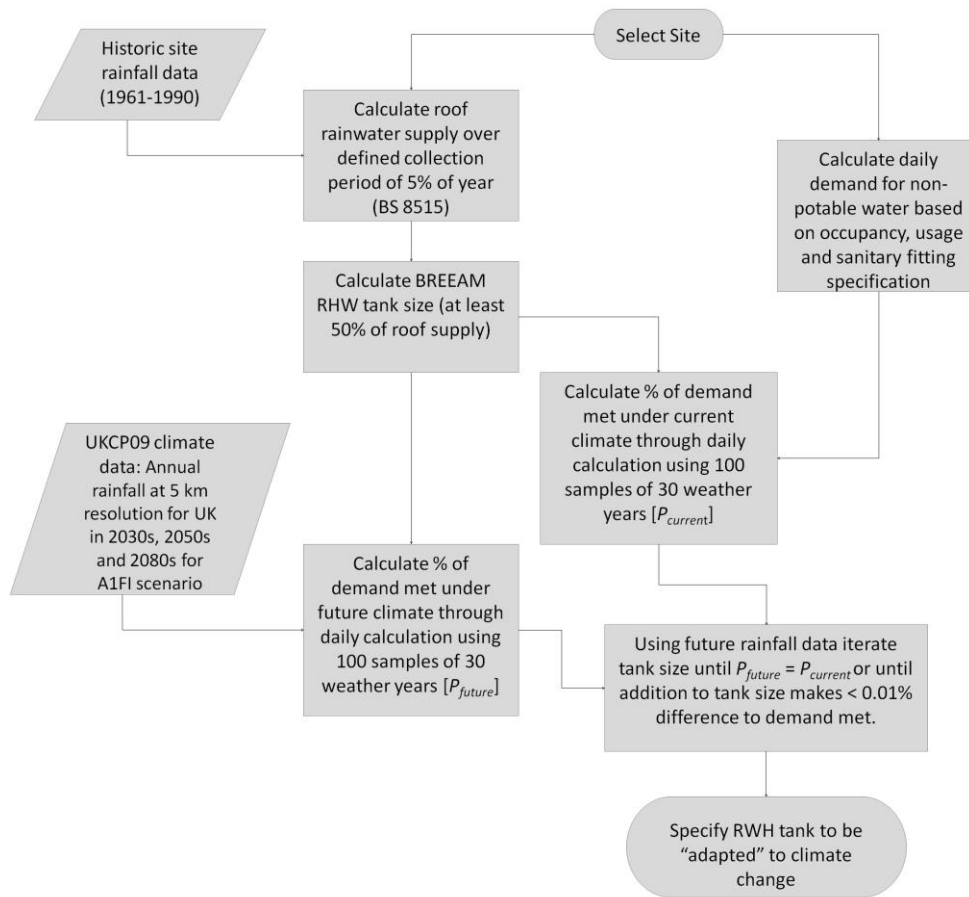


Figure 1 Summary of the methodology undertaken within this paper.

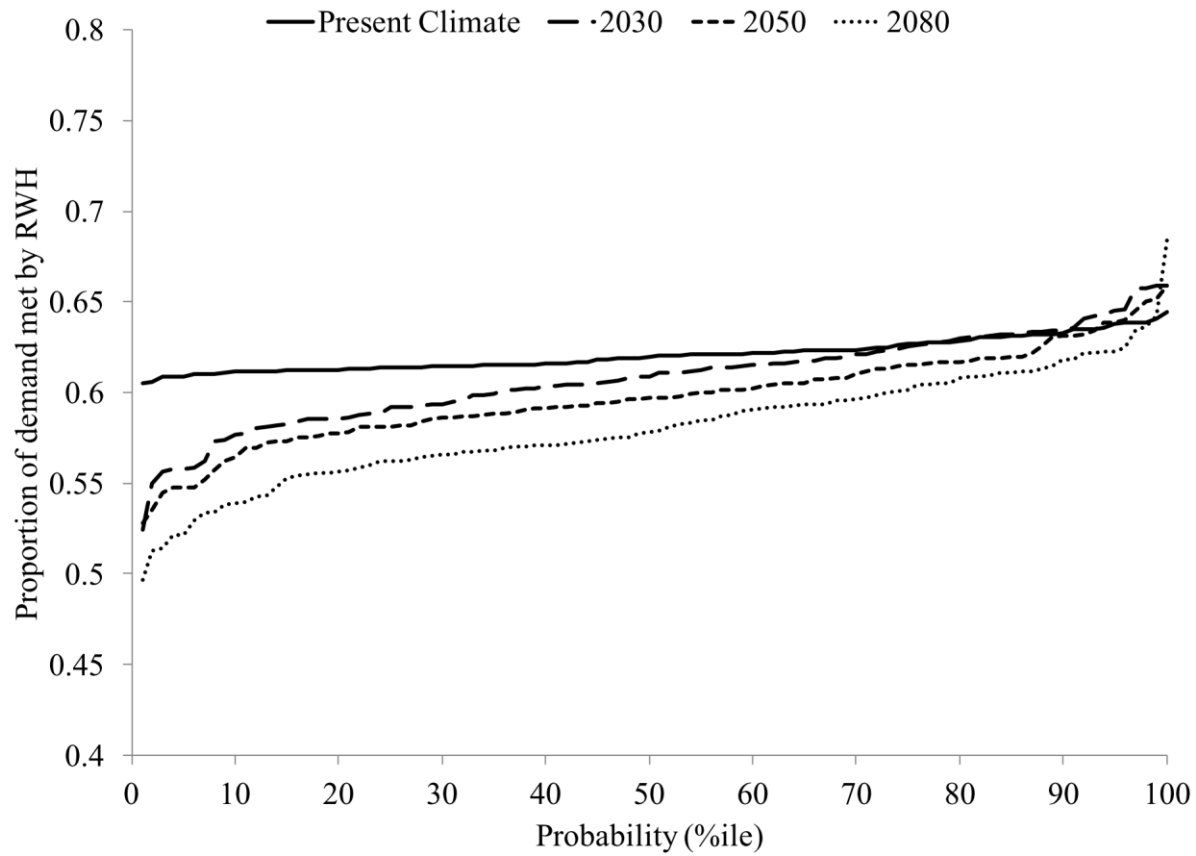


Figure 2 Probability (percentile) that demand met by RWH for the ESI will not be less than the stated proportion for present and future climate scenarios.

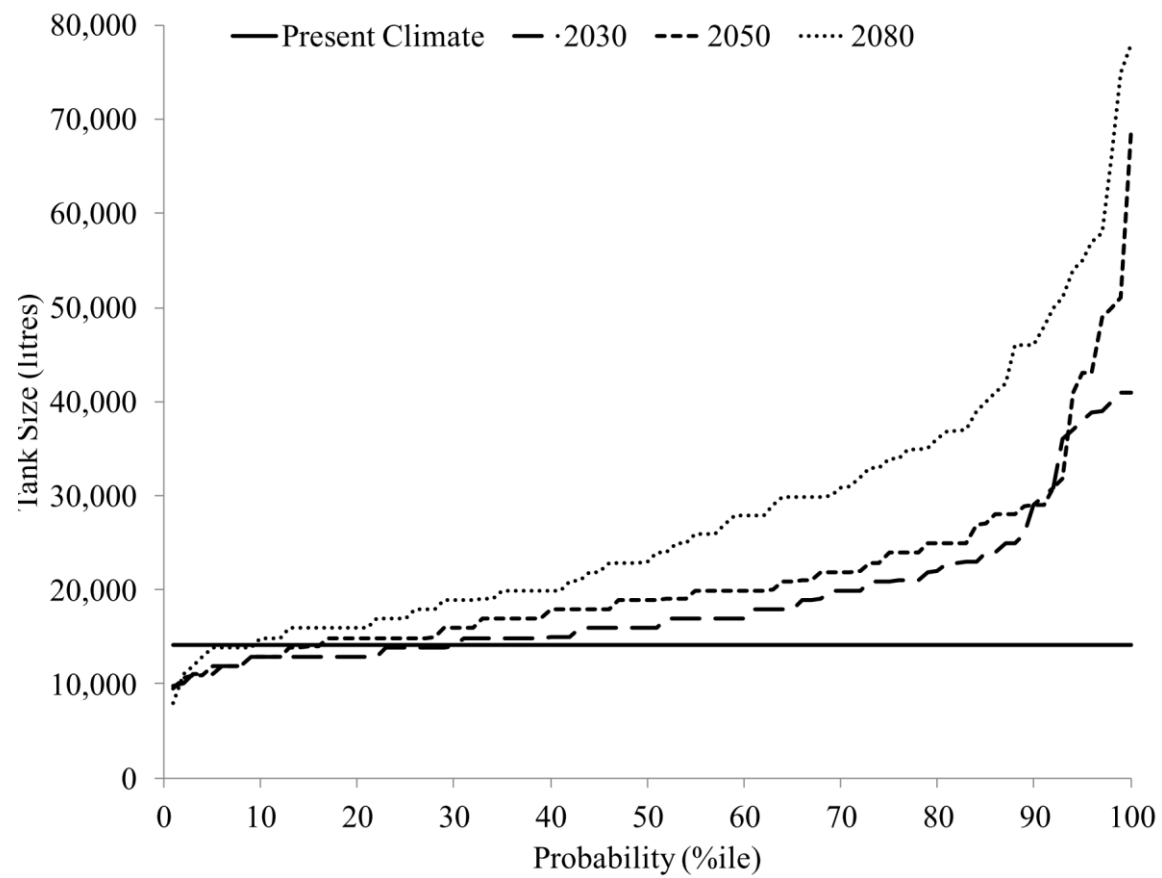


Figure 3 Probabilistic values for ESI tank size to meet current non-potable demand under future climate scenarios.

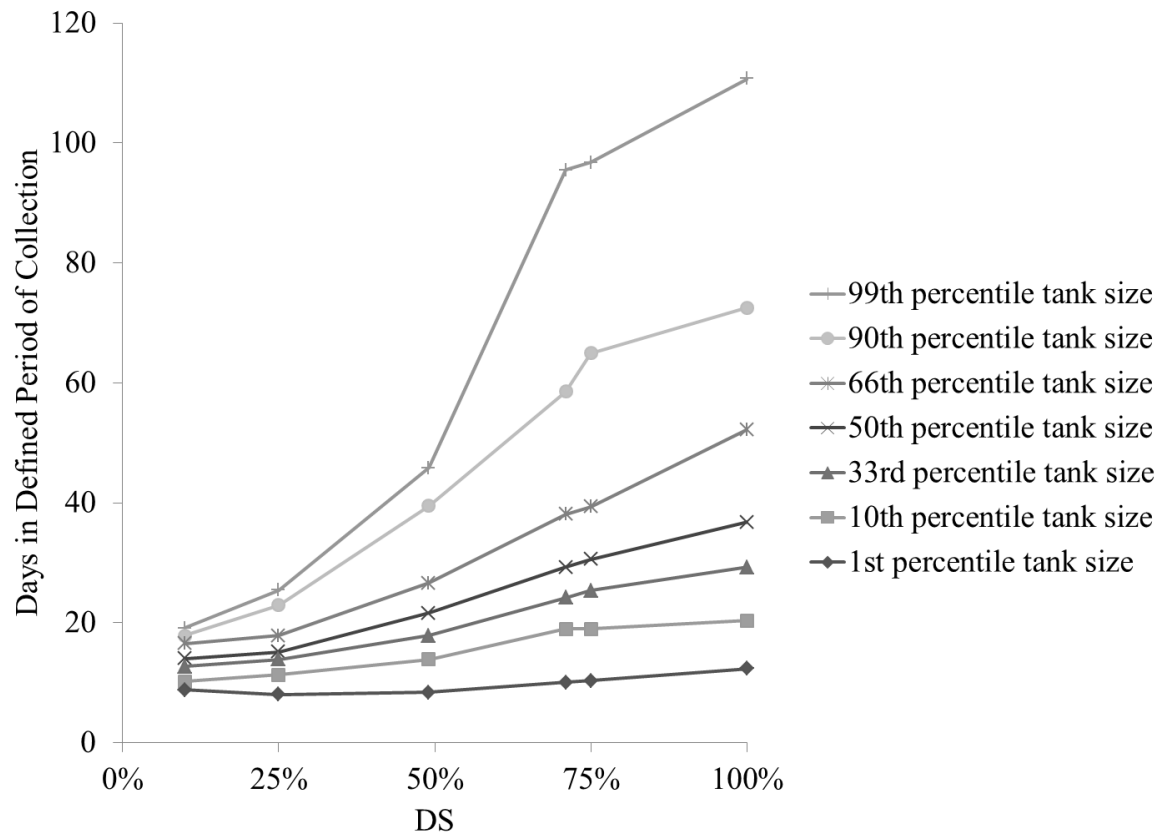


Figure 4 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s in Penryn at different confidence intervals.

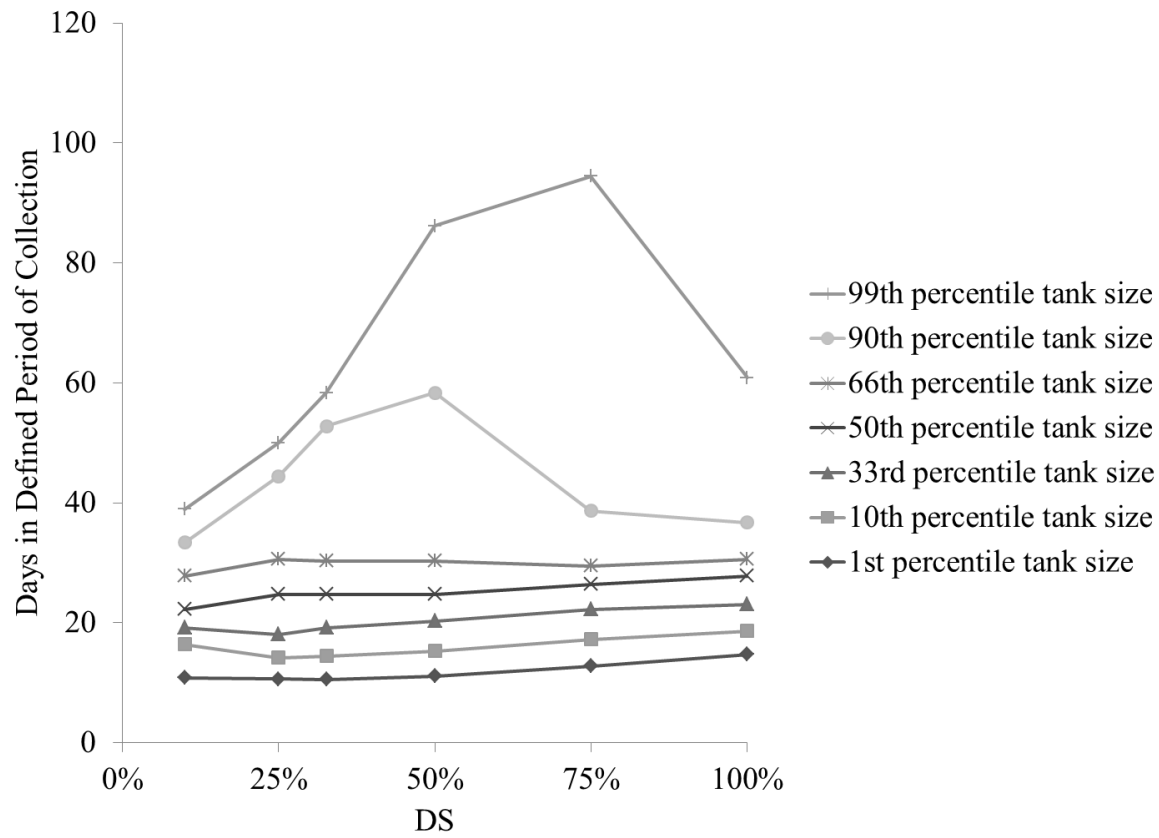


Figure 5 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s in Cambridge at different confidence intervals.

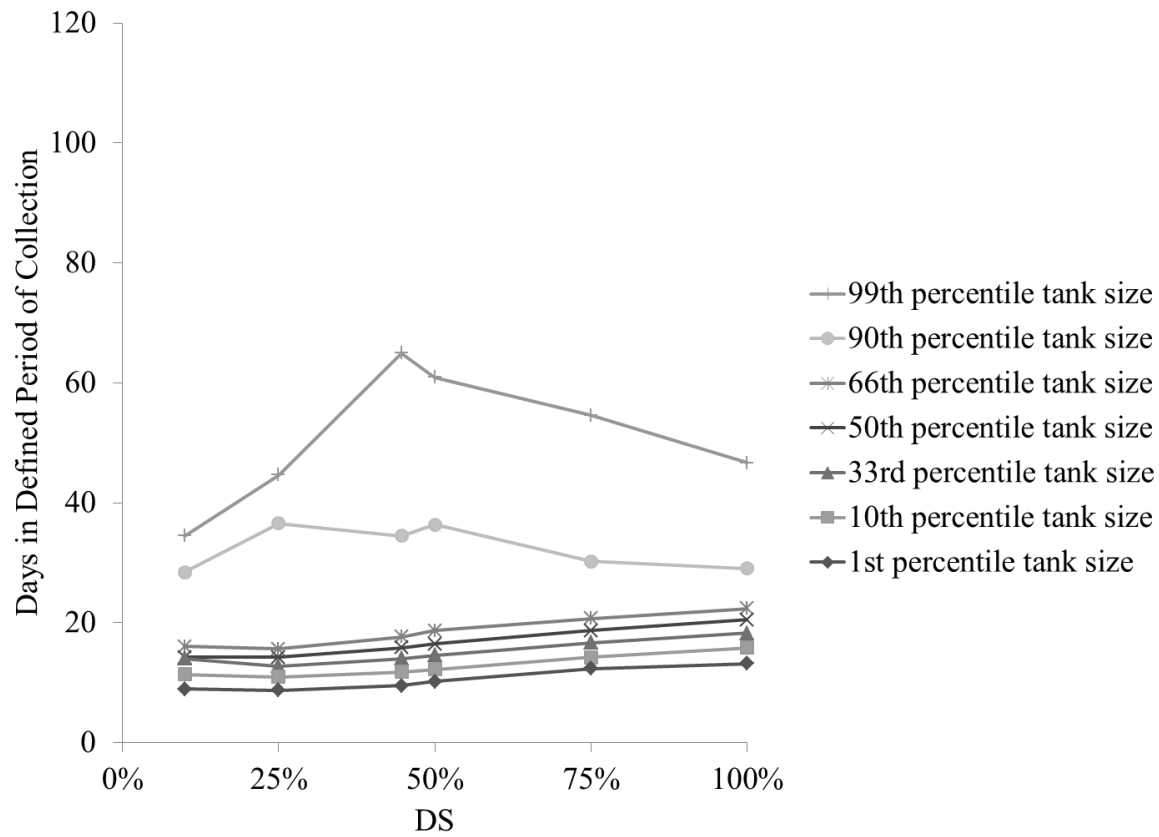


Figure 6 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s in Aberdeen at different confidence intervals.

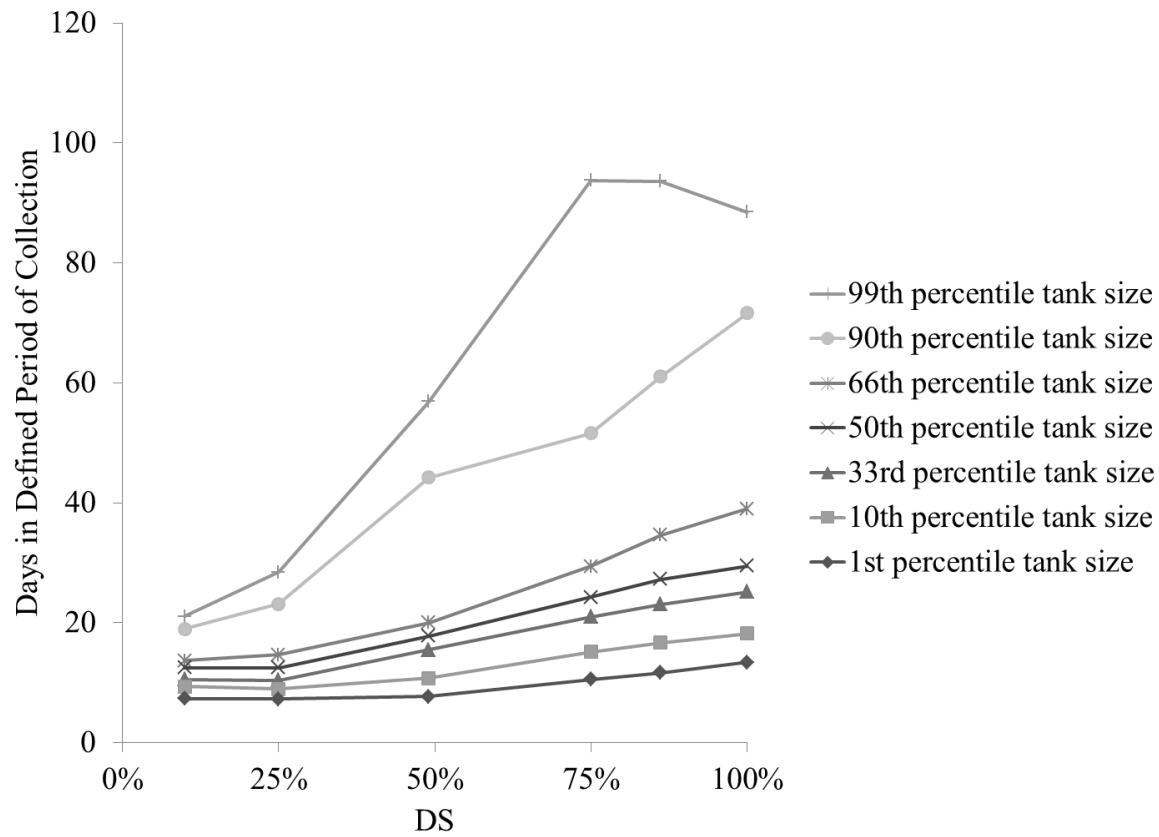


Figure 7 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s in Ammanford at different confidence intervals.

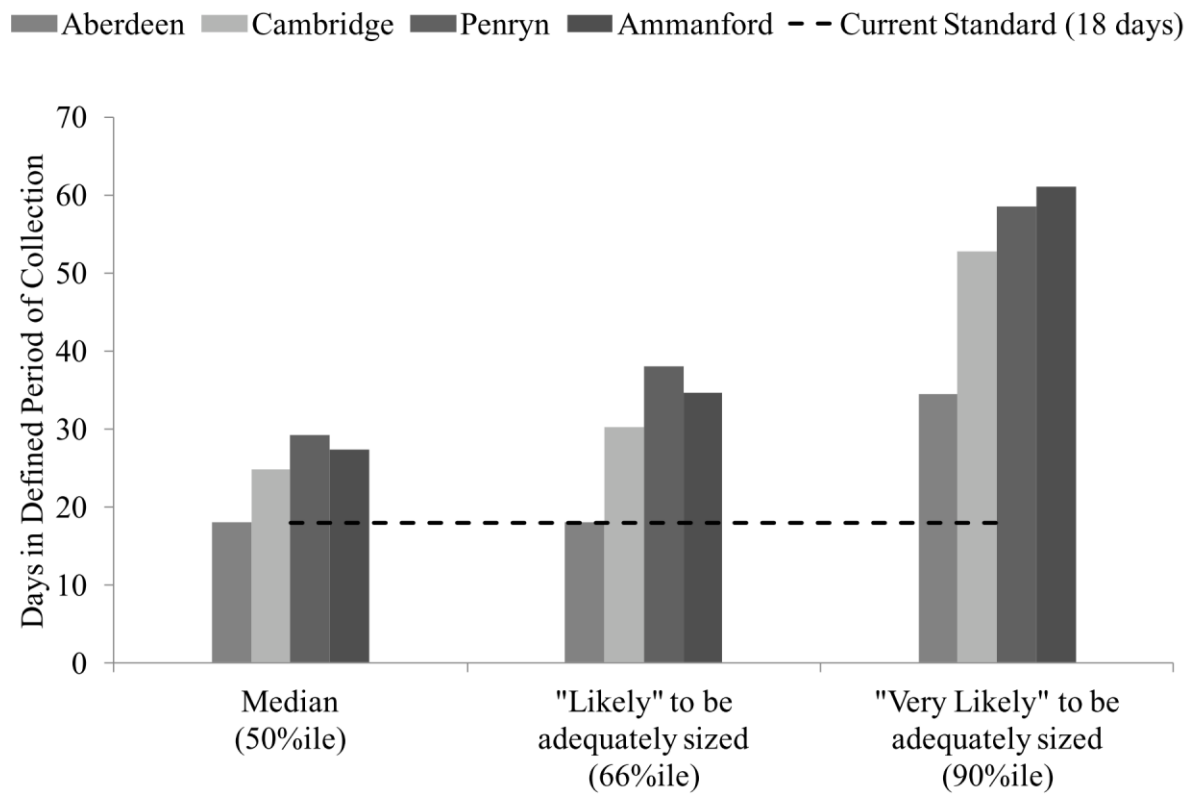


Figure 8 Adjusted number of days in defined period of collection to meet current non-potable demand under climate scenarios for the 2080s at four UK locations at the 50th, 66th and 90th percentile probability levels. The dashed line denotes current practice of using 18 days.

