Irrigation demand modelling using the UKCP09 weather generator: Lessons learned

Short title: Irrigation demand modelling using the UKCP09 weather generator

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ABSTRACT

The determination of irrigation demand is typically based on crop modelling using a long historic record of local daily weather data. However, there are rarely adequate weather station records near to given sites; often any local records cover a limited number of years, are incomplete, costly or are of poor quality.

This paper examines whether version 1 of the UKCP09 weather generator can provide a simpler and effective method of calculating irrigation demand with sufficient accuracy for regulatory and design purposes.

The irrigation demands at seven sites distributed around England were modelled using the UKCP09 baseline climatology and compared to results modelled using daily observed weather records. For the design dry year used for irrigation planning, the weather generator replicated the observed conditions with reasonable accuracy. The weather generator was however less successful at replicating extreme dry years.

These results are encouraging but also provide a note of caution for the use of these generated datasets for studying current irrigation demand and by implication for modelling future needs under

climate change. The study also demonstrated a simple sub-sampling approach for reducing the processing demands if using the dataset in more complex models, though this would not remove any underlying error.

Keywords | irrigation demand, UK, UKCP09, WaSim, weather generator

INTRODUCTION

Water is essential for sustainable development, economic growth and poverty reduction, across a variety of sectors including agriculture, energy, environment and health (Stakhiv & Stewart 2010). A reliable supply is integral to many industries including the irrigated agri-business, and water stress has obvious implications for food production, rural businesses and rural employment (Knox *et al.* 2009; Daccache *et al*. 2011). Water is also expected to be the primary medium through which people, ecosystems and economies will first experience the effects of climate change.

While the volume abstracted for irrigation in the United Kingdom is relatively small, it peaks during the summer months when water resources are most strained, and can create conflict with other demands for water, most notably for the public water supply and environmental protection (Daccache *et al*. 2011). Summer water resources in many catchments are already fully licensed, and some are over licensed or even over abstracted (Knox *et al*. 2010). There is pressure to reduce excessively large licences. Where water is available, applicants for renewal of existing time-limited licences and/or additional abstractions are required to prove a “reasonable need” for the water they request.

Potatoes (*Solanum tubersom L.*) are the most important irrigated crop in the UK, accounting for 43% of the total irrigated area and 56% of the total volume of water abstracted in the UK (Weatherhead 2006; Knox *et al*. 2009). Their sparse root system (85% of the root length is concentrated in the upper 0.3 m soil layer) means they are particularly sensitive to moisture stress (Opena & Porter 1999). The UK potato industry has changed dramatically in recent decades, from a relatively small sector consisting of individual farms to a much larger consortium of major agri-businesses. This shift in production has been principally attributed to rising demand for high quality produce, most easily met by irrigation; this has in turn led to greater interest in irrigation demand modelling across the industry as a whole (Knox *et al*. 2010).

Irrigation demand in a highly variable climate such as the United Kingdom's is best predicted by crop modelling using a long historic daily weather record (generally at least 20 years), precipitation and evapotranspiration being the primary variables of interest (Kilsby *et al*. 2007). Unfortunately, there are rarely adequate weather records near to a given site; local weather stations often cover only a limited number of years, have incomplete or corrupted records, and/or do not record all the variables required to accurately calculate evapotranspiration. There are also significant costs associated with obtaining and validating the data. As a result, the analysis is often based on a synthesis of limited local records with more complete or longer term data from elsewhere, or an interpolation between data from distant stations.

Weatherhead and Knox (2000) developed a procedure for calculating design dry-year irrigation demands (defined as meeting the demand in 80% of years) for use by the regulator in England, the Environment Agency (Mathieson *et al*. 2002). They mapped the country into seven agro-climatic zones based on Potential Soil Moisture Deficit and produced look-up tables for each zone, three soil classes (based on soil water availability) and the major irrigated crop categories. However this procedure reveals little about demand in other years, or how varying farm practices or crop varieties could influence demand.

The United Kingdom Climate Projections 2009 (Jenkins *et al*. 2009), or "UKCP09", dataset provides baseline and future probabilistic climate projections at a 25 km scale resolution generated from a perturbed ensemble experiment using the HadSM3 Global climate model (GCM) and other climate models, but these are only available as monthly values, which is insufficient for modelling supplemental irrigation demand. In contrast, baseline and future daily (and even hourly) projections, and at a finer spatial resolution of 5 km, are available from UKCP09's integrated weather generator

(Jenkins *et al*. 2009). Weather generators, such as the UKCP09 weather generator, have been increasingly used to downscale GCM outputs. They are particularly advantageous as they allow climate variability and uncertainty to be modelled. Historically, they were typically used to supplement observed records, in situations where data is missing or potentially erroneous (Wilks & Wilby 1999). By comparing the weather generator's synthetic series against the observed record we can effectively quantify the skill of a weather generator (Min *et al*. 2011). Once calibrated, weather generators require no manual data input or prior knowledge of climate modelling, allowing for non-specialist end users to better gauge the extent and magnitude of potential impacts associated with climate change. Their growing popularity has in turn led to more widespread uptake across the industry as a whole (Severn Trent Water Ltd 2011).

The UKCP09 weather generator is based around a stochastic rainfall model; other climate variables are then derived from the rainfall state using statistical relationships. Five rainfall states are considered; dry today/dry yesterday, dry today/wet yesterday, wet today/wet yesterday, wet today/dry yesterday and dry today/dry yesterday and dry the day before (Eames *et al*. 2012). It provides statistically credible synthetic climatology that is consistent with the underlying baseline and probabilistic future climate projections (Jones *et al*. 2009). However, it is not intuitively clear that the result will be adequate for modelling irrigation water use, which depends mainly on the frequency and extremeness of dry periods of 10 days or more in a humid climate such as England.

The high spatial and temporal resolution of the UKCP09 weather generator make it an attractive candidate for use with daily soil water balance models such as WaSim (Hess & Counsell 2000) and DSSAT (Daccache *et al*. 2011) which are already being used for irrigation demand estimation. Originally designed as a learning and education aid, WaSim has proven itself invaluable across a range of hydrological studies including determining irrigation requirements, optimising water management and assessing the performance of sub-surface drainage systems (Depeweg & Fabiola Otero 2004; Meenakshi Hirekhan *et al*. 2007). WaSim was selected for this (and other) studies largely on the basis of its flexibility, data availability and demonstrated value as a research tool (Fasinmirin *et al*. 2008; Holman *et al*. 2009).

The UKCP09 weather generator does suffer from certain known limitations (discussion later). While it can be updated and improved (and many of these limitations reduced), it is important to encourage its use for real world decision making (Harris & Bridgeman 2012). However, for this to occur it must be first demonstrated that the UKCP09 weather generator can provide synthetic climate series which are consistent with the observed records and that a decision maker would arrive at the same (or similar) decision had they used the weather generator instead of the observed record. Without this evidence, its continued use for irrigation demand modelling will also be brought into question, with obvious implications for future planning.

This aim of this paper is to establish whether the UKCP09 weather generator can provide an effective tool for irrigation demand modelling which is consistent with the observed record. Two sources of recorded data were considered, from the Met Office's interpolated 5 km grid and directly from weather stations. Generated climate variables at **seven sites** are first compared with the equivalent observed records. The average annual irrigation demand, the 80% dry year demand (following the current best practice approach for irrigation design) and the extreme year demand for a potato crop are then calculated for each dataset. These are compared to establish whether a decision maker would arrive at the same decision if they used the weather generator instead of the observed record.

METHOD

Baseline climatology (1961-1990) is available through the UK Met Office in the form of an interpolated 5 km grid covering the entire UK, derived from the observed record. Thirty-six individual climate parameters are available, including temperature, precipitation, sunshine hours, relative humidity and wind speed. The interpolated grid was generated using inverse-distance weighted interpolation, by means of an irregular spaced and evolving network of observed weather stations

(UK Met Office 2012). However, this database is limited to average monthly values (UK Met Office 2012b). Daily records can be obtained at actual weather station sites from the BADC (British Atmospheric Data Centre 2012).

Climate baselines

Seven sites (Table 1 and Figure 1) were selected to represent a range of agro-climatic conditions, the spatial distribution of irrigated potatoes and on the basis of the quality and completeness of their daily records during the baseline period. For most sites that covered most of the 30 year 1961-1990 baseline period. Baseline observed daily data, and monthly averages at a 5 km grid resolution, were obtained, and duplicate and spurious data entries were removed prior to data processing. Evapotranspiration was derived using Penman-Monteith (Monteith 1965), using the period 1969-1990 due to the lack of earlier wind speed data for the interpolated grid

Table 1 Weather station sites and records used

Station name	Station ID	Elevation(m AOD)	Latitude	Longitude	Data from	Data to
Brooms Barn	435	75	52.260	0.567	1/1/1964	31/12/1990
Carlisle	1070	26	54.934	-2.962	1/1/1961	31/12/1988
Ringway	1135	69	53.356	-2.279	1/1/1963	31/12/1990
Shawbury	643	72	52.794	-2.663	1/1/1962	31/12/1990
Slaidburn	507	192	53.987	-2.433	1/1/1961	31/12/1990
Terrington	406	2	52.745	0.290	1/1/1963	31/12/1990
Woburn	458	89	52.014	-0.595	1/1/1961	31/12/1990

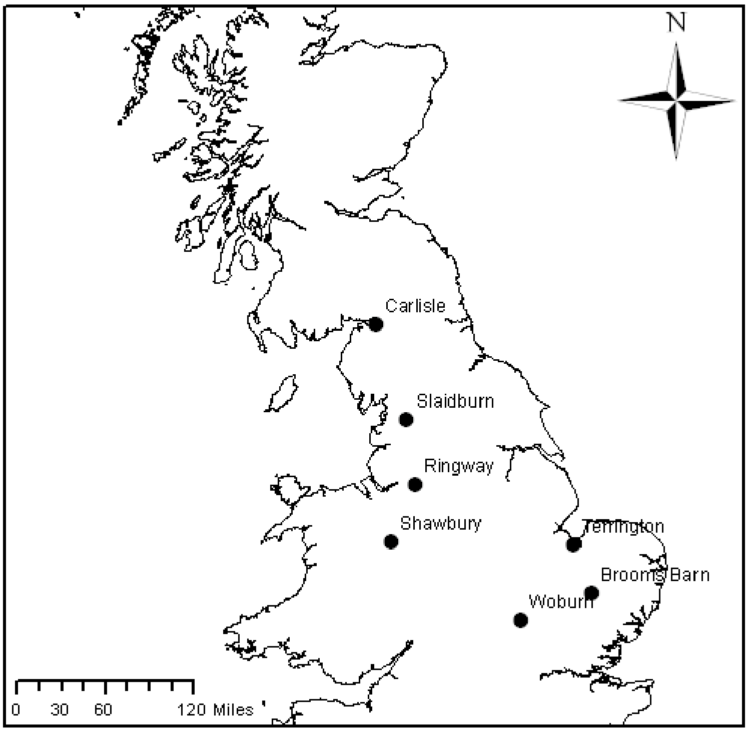

Figure 1 Weather station sites

UKCP09 weather generator

The UKCP09 weather generator provides statistically equivalent 30 year daily weather sequences for any given time slice and emission scenario of interest. The UK Climate Impacts Programme (UKCIP) suggest a minimum of 100 sequences should be used in analyses and modelling. For this study, therefore, 300 control (baseline) sequences were generated for each of the 5 km pixels where the seven sites are located using version 1 of the UKCP09 weather generator. This corresponds to 100 sequences for each of the three climate change scenarios (although the baseline sequences without climate change are of course equivalent). Whether fewer sequences would give similar results is discussed later.

As an initial check, the weather generator baselines were compared to the observed record at each weather station in terms of a) monthly precipitation and b) monthly evapotranspiration, given the importance of these variables for modelling irrigation demand.

The weather generator baselines values were then compared to the Met Office's interpolated grid values. Statistical analysis, using a Mann Whitney U-test, was undertaken in order to establish whether there was a significant difference in these basic parameters between the weather generator outputs, the observed records and the interpolated grid.

Irrigation demand

Next, WaSim was used to model irrigation demand at each site. WaSim undertakes a multi-layer one-dimensional, daily, soil water balance, it simulates inflow (infiltration) and outflow (evapotranspiration and drainage) and storage of soil water in response to climate, irrigation and drainage (Depeweg & Fabiola Otero 2004). WaSim divides the soil profile into five layers, water moves from upper layers to lower layers when the water content of the respective layer exceeds field capacity. The first three layers are comprised of the surface layer (0-0.15 m), the active root zone layer (0.15-root depth) and the unsaturated layer below the root zone (root depth-water table). The remaining two layers are comprised of the saturated layer above drain depth (water table – drain depth) and the saturated layer below drain depth (depth drain – impermeable layer). The boundary between the second and third layers will change in response to root growth (e.g. in the case of potatoes, layer 2 will have zero thickness when root depth is less than 0.15 m, and will then increase as the potato develops).

WaSim requires rainfall and evapotranspiration data in order to run. An additional utility, WaSimET, is available for calculating evapotranspiration from climate data using Penman-Monteith, Food and Agriculture Organisation (FAO) Modified-Penman or Penman methods. Guidance values covering crop development and root depths are provided for selected crops within WaSim, and up to three crops to be combined in a cropping pattern (Hess & Counsell 2000). Root development is assumed to increase from the planting depth to the maximum depth following a sinusoidal curve between the planting date and the maximum root date. Irrigation schedules can be set up as either calendar or rule based. Calendar schedules assume a fixed irrigation date (e.g. 30 days after planting – irrigate 60 mm), whereas rule based scheduling, used in this study to simulate actual farmer behaviour in England, divides the cropping season into a series of irrigation and non-irrigation periods on the basis of rules governing the frequency and volume of irrigate application. In its basic format WaSim is not capable of processing multiple climate files succinctly, so a modified version was developed and employed for this study to speed up data processing.

A potato crop was simulated with a planting depth of 0.15 m, max root depth of 0. 7m and planting date of 1st April. An irrigation schedule was chosen based on best practice guidelines including scab control (Defra 2005). This schedule consisted of 4 periods (1 non-irrigation followed by 2 irrigation and 1-non irrigation), applying 15 mm of irrigate early in the growing season when the root zone deficit exceeded 18 mm during period 2 (15th May-30th June) and applying 25 mm irrigate when the root zone deficit exceeded 30 mm during period 3 (30th June-31st Aug). Irrigation early in the growing season is essential for some varieties for minimising the chance of potato scab, a common bacterial blight which can severely reduce the market value of produce (Liu *et al.* 1996). Irrigation is also important for promoting higher tuber numbers, accelerating crop canopy growth, reducing the chance of uneven growth and thumbnail cracking and reducing crop damage during harvesting (Defra 2005). The soil type was set as sandy loam, which is the dominant soil type for potato crops in England, with an assumed saturation of 43.3% and field capacity of 24.5%. In reality soil types will differ between the investigated sites, though for the purpose of this study they were assumed to be the same for consistency.

At each site, the annual irrigation demand was calculated each year in the 300 x 30 year generated sequences and for the observed weather record. Statistical analysis, using a Mann Whitney U-test, was then undertaken to establish whether there was a significant difference between the average annual irrigation demand and inter-annual standard deviation from the weather generator sequences and the observed record. Transformations were subsequently applied where the data was not normally distributed. If it was still not normally distributed, a non-parametric test (Mann

Whitney U-test) was used. Where the data was normally distributed, either before or after transformation, a 2 sample T-test was used.

Each sequence was then ranked from smallest to largest based on the annual irrigation demand; for the 300 generated sequences this gave 300 values for the "driest" year, the second driest etc. The 80th percentile design dry year values were then identified, and again compared to the observed values. The extreme dry year values were similarly compared.

Finally, a short study was undertaken to establish whether it would be possible to use fewer weather generator sequences and still obtain reasonable accuracy. The following equation, (e.g. Lohr 1999) was applied.

$N_0=z^2(s^2/e^2)$

Where: N = minimum sample size

z (for 95% Confidence Interval) = 1.96

S= standard deviation

e= error coefficient

RESULTS

Climate baselines

The results revealed that the observed and weather generator datasets of monthly average precipitation and evapotranspiration were significantly different at the majority of the sites (Table 2). The observed record also exhibited a much larger precipitation standard deviation than the weather generator at all the sites (e.g., Figure 2). Observed and weather generator average monthly precipitation was significantly different at the 95% confidence interval at the majority of the sites. The weather generator and interpolated grid values also provided significantly different results at the majority of sites. These findings were unexpected given that the weather generator was itself calibrated on observed daily rainfall totals and other weather variables.

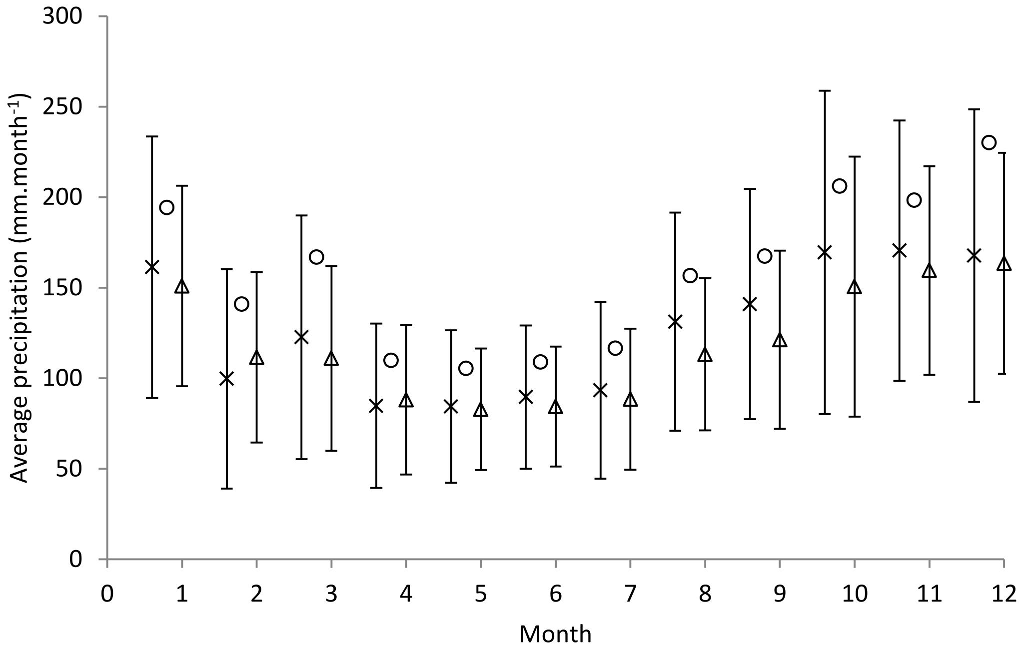

Figure 2. Monthly precipitation at the Slaidburn site for the baseline period 1961-1990, comparing observed weather station records (X), weather generator datasets (Δ) and interpolated grid values (o). Error bars represent one standard deviation above and below the observed and average weather generator record.

Table 2 Test for significant differences comparing observed and weather generator monthly precipitation and monthly evapotranspiration and interpolated grid and weather generator monthly precipitation and monthly evapotranspiration at the 95% confidence interval for all seven sites.

	Precipitation p-value	
Site	Observed versus weather generator	Interpolated grid versus weather generator
Brooms barn	0.002	0.000
Carlisle	0.068	0.315

Ringway	0.000	0.000
Shawbury	0.002	0.432
Slaidburn	0.495	0.000
Terrington	0.092	0.269
Woburn	0.000	0.000

	Evapotranspiration p-value	
Site	Observed versus weather generator	Interpolated grid versus weather generator
Brooms barn	0.004	0.131
Carlisle	0.033	0.005
Ringway	0.000	0.000
Shawbury	0.002	0.027
Slaidburn	0.071	0.000
Terrington	0.008	0.398
Woburn	0.018	0.014

Irrigation demand

Results from the analysis of average annual irrigation demand are shown in Figure 3. The weather generator results are within one 25 mm application (the depth of a typical single application) of the annual irrigation demand computed from the observed record at all the sites except Ringway, which recorded a difference of 35 mm (equivalent to 27% difference).

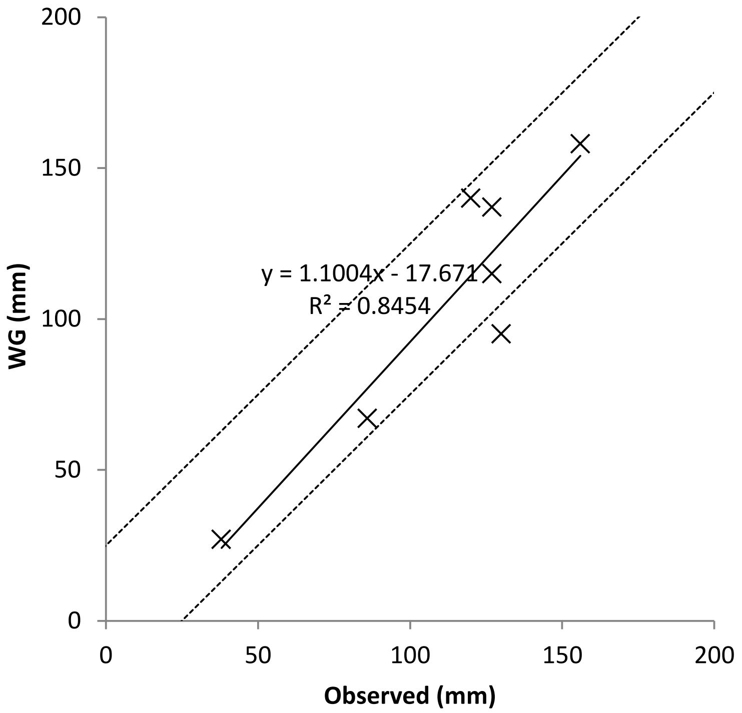

Figure 3 Average annual irrigation demand for all seven sites modelled using the observed and weather generator datasets. Dotted lines indicate +/- 25mm error on observed baseline, Ringway is the only outstanding site. Best fit trend line is included.

Statistical analysis, using a combination of Man Whitney U-test (MWUt) and 2-sample T test (2Tt) showed that the observed and weather generator values for the average annual irrigation demand were not significantly different at any of the investigated sites (Table 3). Significant differences were however recorded in the inter-annual standard deviation at two sites, Carlisle and Ringway.

Table 3 Test for significant differences comparing observed and weather generator average annual irrigation demand and inter-annual standard deviation at the 95% confidence interval for all seven sites.

	Average annual irrigation demand		Inter-annual irrigation demand standard deviation	
Site	Statistical analysis	P-value	Statistical analysis	P-value

Brooms barn	2Tt	0.882	2Tt	0.809
Carlisle	2Tt	0.095	2Tt	0.015
Ringway	2Tt	0.063	2Tt	0.011
Shawbury	2Tt*	0.669	2Tt	0.291
Slaidburn	MWUt	0.499	MWUt	0.355
Terrington	MWUt	0.142	2Tt	0.092
Woburn	2Tt	0.557	2Tt	0.727

*Transformed data

The observed and weather generator annual irrigation demands, plotted against probability of non-exceedance, are shown in Figure 4. It should be noted that the discrete depths of water applied (15 mm and 25 mm) accounts for the steps in the observed weather results, whereas these are smoothed out by the averaging of 300 sequences for the weather generator results.

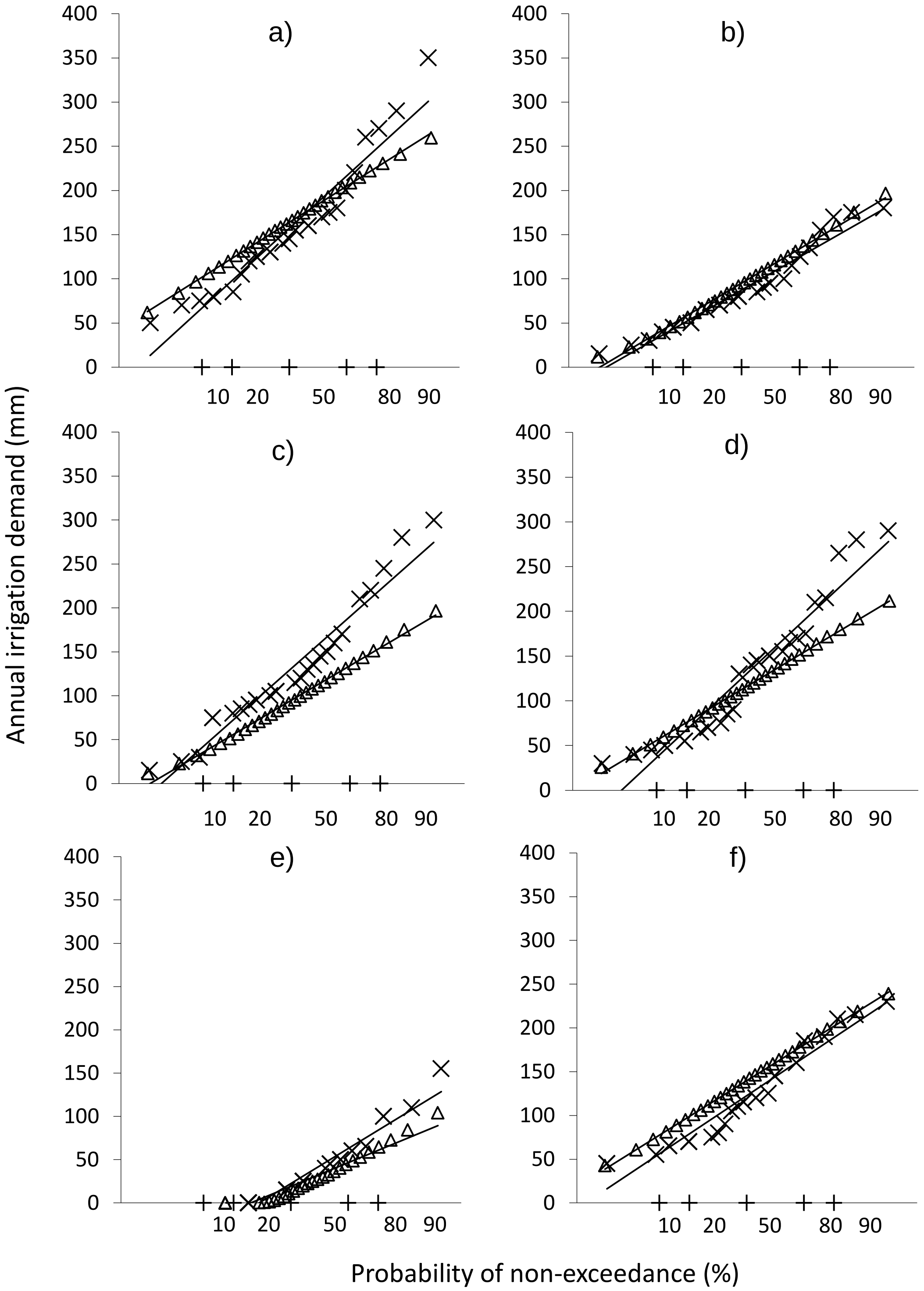

Figure 4 Annual irrigation demand against probability of non-exceedance for the baseline period for Brooms barn (a), Carlisle (b), Ringway (c), Shawbury (d) Slaidburn (e) and Terrington (f) comparing results from observed (X) and weather generator datasets (Δ). Results for Woburn are shown in figure 5.

Hence the weather generator appears reasonably successful in modelling the annual irrigation demand in normal years, with the exception of at Ringway, which could be the result of an unusual micro-climate at this particular site. It underestimates the observed conditions during the driest years at the majority of the sites. This may reflect the occurrence of the extreme dry years 1975 and 1976 in the observed dataset. Even the most extreme results in the 300 sequences did not reach the values for these exceptionally dry years at all sites, for example at Woburn (Figure 5).

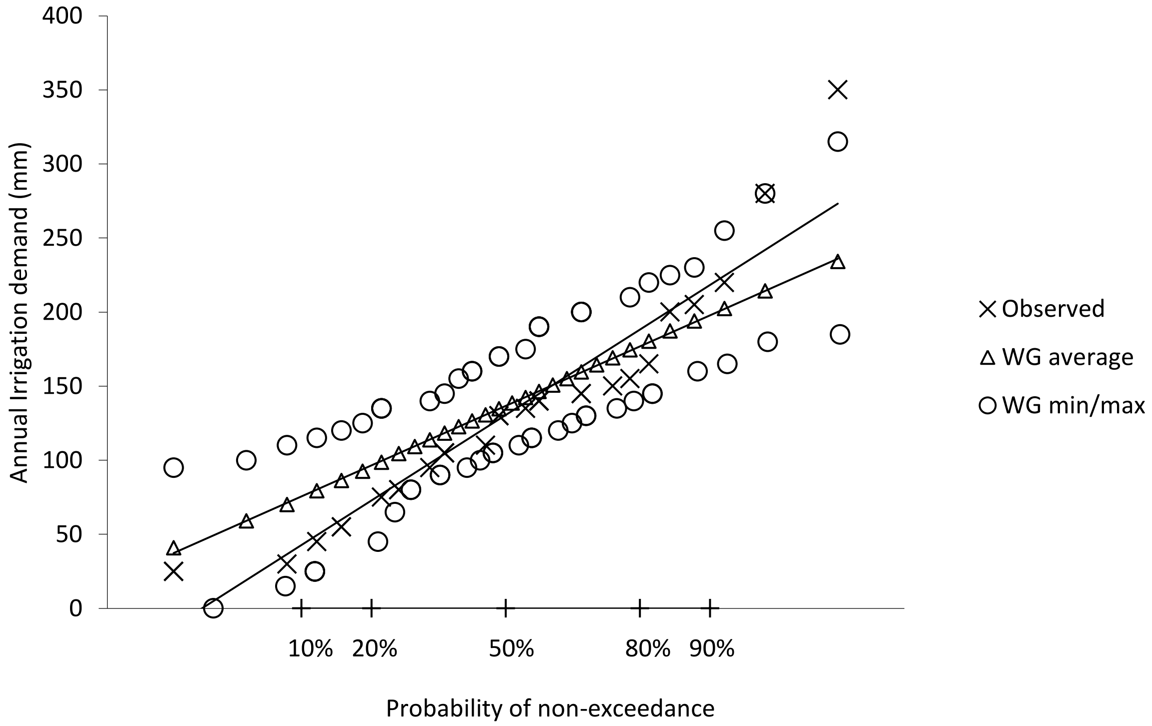

Figure 5 Woburn annual irrigation demand against probability of non-exceedance for the baseline period 1961-1990 observed (X) and weather generator average (Δ) and weather generator max/min respectively. 80% represents the current best practice approach.

A design dry year for allocating agricultural water resources and designing irrigation systems and storage reservoirs in the UK is typically taken as one with an 80% probability of non-exceedance, roughly equivalent to the older concept of the "fourth driest year in five" (Weatherhead & Knox 2000). The weather generator was largely successful in replicating the observed dry year values

(Table 4). The average of the 300 weather sequences was within 25 mm at all but one of the sites, Ringway. The average weather generator value tended to be lower than the observed baseline value.

Table 4 Design dry year (80% probability of non exceedance) irrigation demand (mm) for the seven sites for the baseline period, calculated using the observed and weather generator dataset respectively.

	80% probability of non-exceedance event			
		Weather generator (300 sequences)		
Site	Observed	Average	Range	Standard deviation
Brooms barn	196	198	165-236	12
Carlisle	121	99	71-131	11
Ringway	170	132	105-171	12
Shawbury	172	152	116-187	11
Slaidburn	61	50	25-86	10
Terrington	175	179	145-217	12
Woburn	157	176	141-212	12

The study used 300 sequences, based on the recommendations of UKCIP. Analysis showed that it is theoretically possible to use far fewer weather generator sequences and still remain confident that the average and design dry year values are reasonably reflective of the full population (Table 5). For estimating annual irrigation demand with a 25 mm acceptable error - at the 95% confidence interval, required just 2 sequences at most sites, and only 1 at Slaidburn. Decreasing the acceptable error to 10 mm led to an increase to 4 sequences at most sites. Similar results were recorded with the 80% design dry year, with most sites requiring 2 sequences and 5 sequences respectively. Using the equation does require a degree of hindsight about the standard deviation, but this could be estimated using a simple model such as WaSim, before using a more complex crop model. However, there are limitations to the use of this equation, and it is strongly recommended that more sequences than these values are used to give confidence in the results.

Table 5 Minimum number of weather generator sequences at the 95% confidence interval, generated using the standard deviation of 300 weather generator sequences and an error coefficient of 10 mm and 25 mm respectively.

	Average annual irrigation demand		80% percentile design dry year	
Sample size (N_0)	Error coefficient (e)		Error coefficient (e)	
Site	10 mm	25 mm	10 mm	25 mm
Brooms barn	4	2	5	2
Carlisle	3	2	5	2
Ringway	4	2	5	2
Shawbury	4	2	5	2
Slaidburn	2	1	4	2
Terrington	4	2	5	2
Woburn	4	2	5	2

CONCLUSIONS

Findings of this study first demonstrated that the version 1 of the UKCP09 weather generator performed poorly when replicating observed precipitation and evapotranspiration, based on both recorded weather station and interpolated grid data. This was unexpected considering that the UKCP09 weather generator was originally calibrated on the Met Office's interpolated grid, itself created from the UK's weather station network. The weather generator was noticeably worse at reproducing observed evapotranspiration than precipitation, while both weather generator variables were generally closer to the point measurements compared to the interpolated grid.

Nevertheless, the study has demonstrated that the weather generator was reasonably successful at replicating the average annual irrigation demand, the annual variation in observed irrigation demand and the design dry year demand (based on the 80% probability of non-exceedance event). The weather generator was less successful at replicating the driest years in the recorded dataset, but these were exceptionally dry years. Previous studies have identified similar limitations in the weather generator's ability to reproduce extreme events. The UKCP09 weather generator is unable to recreate blocking regimes effectively, which themselves can lead to extended heat waves, exceptionally cold winters and droughts with obvious implications for irrigation demand modelling (Jones *et al*. 2009). While improvements have been made, large return period events should still be treated with caution (Harris & Bridgeman 2012). Its limited ability to recreate extreme events is unlikely to impact the decision making process in the irrigation context, but could be more significant in other applications. This study did not consider whether the UKCP09 weather generator could successfully reproduce observed day-to-day operations at field level (i.e. when and how often to undertake irrigation). However, given the highly variable day-to-day climate in the UK it is very unlikely that the UKCP09 weather generator would be capable of doing so, though further work is recommended to test the validity of this assumption. In addition, further work is recommended to establish whether or not later versions of the UKCP09 weather generator improve the reproducibility of observed conditions.

The findings of this study have demonstrated the potential value of the weather generator as an alternative and potentially more accessible source of baseline daily data for irrigation and water resource planning, but highlight the need for caution. The generated climate data can be downloaded from UKCP09 in the absence of sufficient baseline data, and is particularly useful for sites where data is considered to be poor quality or suspect. The weather generator output also contains additional probabilistic climate information, represented by the variation between sequences in the average annual irrigation demand and 80% design dry year. This data is not particularly useful for analysing irrigation demand during the baseline period but would be directly applicable to modelling the future (Green & Weatherhead 2013), giving some (partial) indication of climate variability and uncertainty. In addition, future studies using the UKCP09 weather generator (such as Green & Weatherhead 2013) can be considered more robust, at least at these particular sites, now that it has been demonstrated that the weather generator can effectively recreate the observed baseline demands.

The study has also demonstrated that it is feasible to use fewer weather generator sequences and still remain confident that any subsequent conclusions drawn from the design dry year are reflective of a much larger sample, although any underlying differences with observed values will still remain. While determining the minimum number of sequences does require some degree of hindsight about the standard deviation, and is unnecessary for relatively simple models like WASIM, this should prove of interest to modellers using more complex models that cannot process and subsequently interpret the large number of weather generator sequences used in this study.

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