High level review of the Optimum Water Use methodology for agriculture following the 2018 drought in England

Technical Briefing Note

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1. Context

After a spate of relatively average to ‘wet’ summers in England from an irrigation perspective, the heatwave and protracted dry conditions in 2018 highlighted the significant agronomic and economic importance of water resources for agricultural irrigation and the risks to production that can arise when abstractions are restricted.

From an abstraction licensing perspective (licensed volume and reasonable need) 2018 also provides a useful ‘reference’ year against which actual irrigation applications (depths applied) can be compared against theoretical ‘design’ dry year requirements. It also offers an opportunity to gather feedback from abstractors on their management practices, how they coped with the drought conditions and any lessons learnt in order to support the EA in providing abstractor guidance to support improved decision-making in future drought years.

Following discussion with EA staff, this short study was commissioned to produce a Technical Briefing Note for the irrigated agriculture sector in England ahead of the 2019 spray irrigation season. The intention was that the report would include a brief agroclimatic assessment of 2018 and provide additional information to complement the EA Spray Irrigation (SI) Prospects Information which is distributed to abstractors each year. This Technical Briefing Note summarises the aim and objectives of the study, the methodological approaches developed and the key findings that emerged from the analyses.

2. Study scope and objectives

The study had three main components:

1. To review and assess 2018 against the ‘design’ dry year definition - as used in the Optimum Water Use methodology (Weatherhead et al., 2002) - to put 2018’s irrigation abstractions in context and to enable SI abstractors to understand the differences between a ‘drought’ year and a ‘design’ dry year;
2. To identify any specific areas within the Optimum Water Use methodology for outdoor crops that might require revisiting and updating in the near future, taking account of changes in farming and irrigation practices over the last 15 years, and;
3. To consider how irrigation abstractors might better plan and manage against future drought events such as 2018, taking into account that increases in licensed quantities are often not a sustainable option due to environmental constraints. This would include identifying alternative water resource options and their viability, the emerging innovations in precision irrigation and opportunities for promoting more collaborative approaches to water management (e.g. sharing/trading water within abstractor groups).

3. Approach

The study was desk based, drawing on existing research information principally from previous research and combining this with agroclimatic modelling to assess 2018 in irrigation design terms. In addition, a number of telephone interviews and a short email questionnaire were circulated to a sample of growers to elicit their feedback and opinion on the effects of the 2018 drought on their irrigation practices and business. The methodology involved the following steps:

1. Following discussion with the EA, 9 representative weather stations with long-term daily historical climatology (rainfall and reference evapotranspiration, ET) were selected. The stations needed to be in close proximity to areas of concentrated irrigation demand and have a near complete record of historical meteorological observation data including 2018.
2. There are a number of drought severity indicators used internationally to assess the magnitude and impacts of drought on agriculture (and other sectors). For England, an agroclimate indicator termed maximum potential soil moisture deficit ($PSMD_{max}$) was used (Knox et al., 1996). This has been used in many previous studies to assess irrigation needs in England and is embedded within the methodology used by the EA for assessing and reviewing abstraction licences (reasonable need). The $PSMD_{max}$ indicator was used to compare the weather in 2018 at each weather station site against the 'design' dry year - defined as being a year with an 80% probability of non-exceedance of $PSMD_{max}$. Internationally, the World Meteorological Organisation (WMO) has defined the Standardised Precipitation Index (SPI) as being the benchmark drought severity indicator for comparing the intensity of individual drought years. It can be calculated for varying monthly 'lags'. SPI data for a selected site are also provided for comparison.
3. The spatial and temporal variances in agroclimate ($PSMD_{max}$) were then analysed using the weather station sites, to assess how the weather varied geographically in 2018 across England and also over the past 30-40 years. This was to help put 2018 in context with previous drought or very dry years.
4. A short email questionnaire to approximately 30 growers was sent out to gather information on their irrigation practices and applications in 2018 for comparison against the equivalent 'design' dry year estimates. This email enquiry was supported by a small number (c10) of detailed interviews (telephone and face to face) with abstractors to gather specific evidence on their experiences of 2018 in terms of irrigation management, crop production impacts and lessons learnt regarding future water resources planning.

4. Comparison of 2018 drought and the 'design' dry year definition

4.1 Reference weather stations

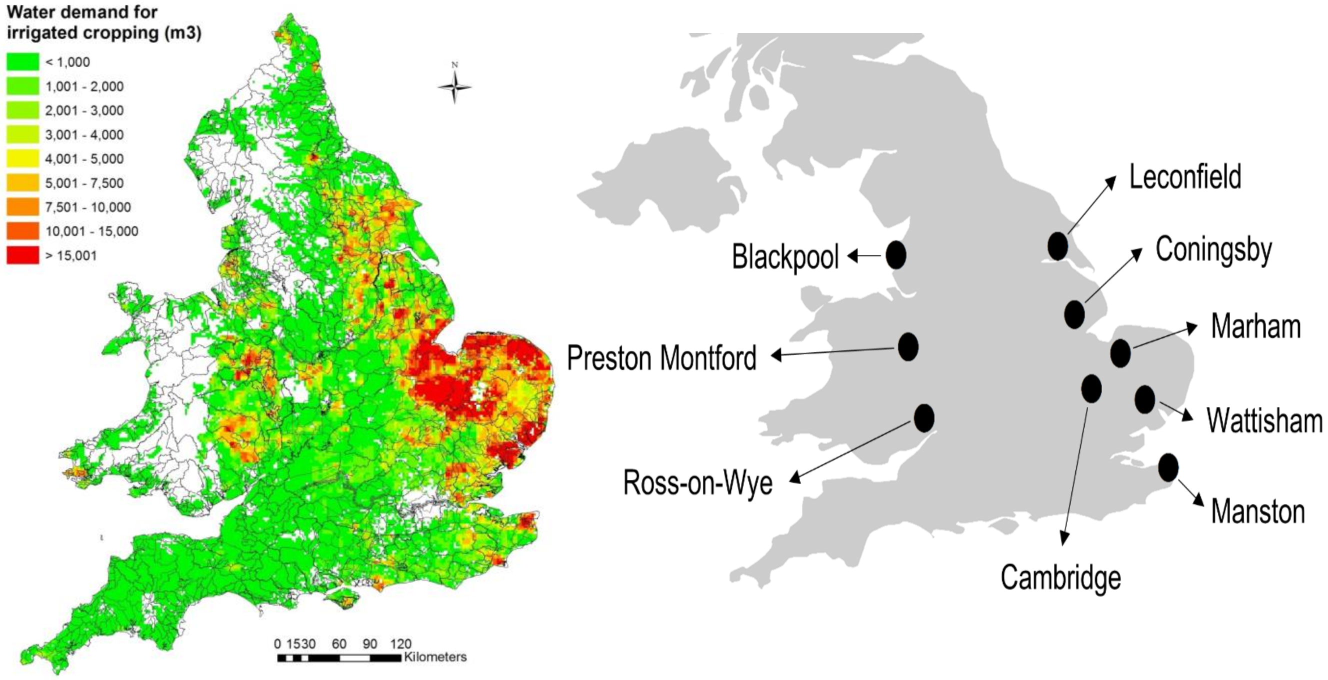
Following discussions with the EA, 9 weather stations were selected. These were based on their use in previous EA irrigation studies, and their suitability to capture the range of agroclimatic conditions across England for locations where irrigated production was concentrated (Table 1). Daily weather for 1962 – 2018 was collated for each station, including: rainfall, and air temperature, sunshine, dewpoint temperature and wind speed (required to reference evapotranspiration, ETo). Short periods of missing data were extrapolated from surrounding days. For longer periods, data were obtained from nearby stations.

Table 1 Weather stations used for assessing 2018 conditions and irrigation needs.

Station ID	Station	Latitude °	Longitude °
370	Leconfield, Yorkshire	53.8744	-0.44009
393	Coningsby, Lincolnshire	53.0935	-0.17119
409	Marham, Norfolk	52.6510	0.56772
440	Wattisham, Suffolk	52.1234	0.95910
775	Manston, Kent	51.3460	1.33716
455	Cambridge, Cambs	52.2450	0.10196
671	Ross-on-Wye, Herefordshire	51.9108	-2.58441
638	Preston Montford, Shrewsbury	52.7243	-2.84043
1090	Blackpool, Lancashire	53.7746	-3.03647

The location of each weather station relative to the main areas of outdoor agricultural irrigation demand is shown in Figure 1.

Figure 1 Spatial distribution of irrigation demand (Knox et al., 2015) and location of reference weather stations.

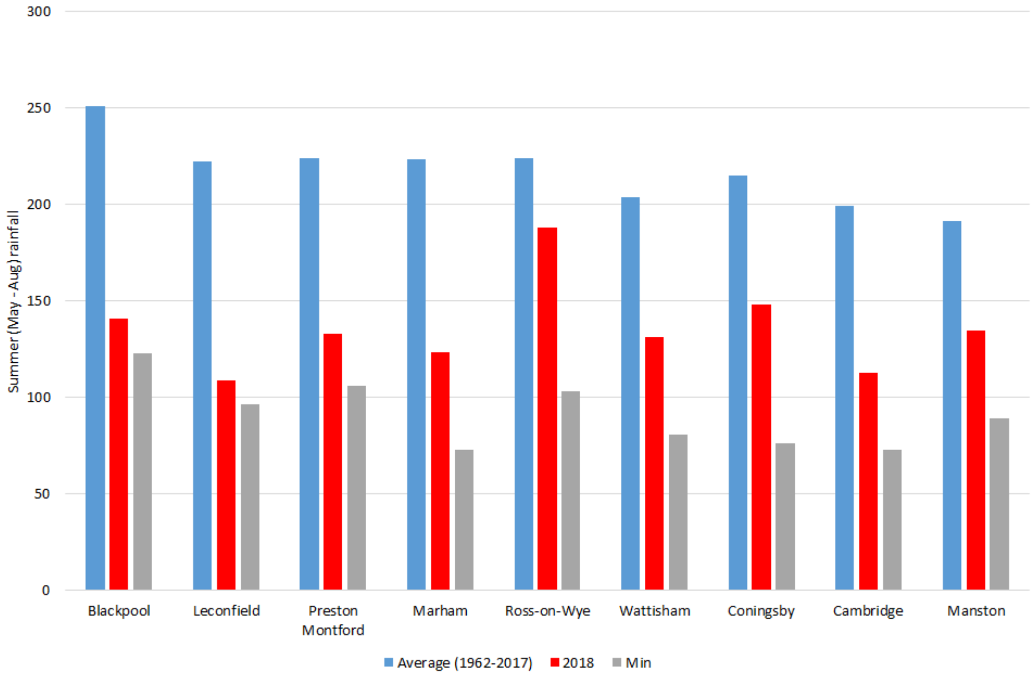


In humid countries such as England, irrigation is supplemental to rainfall, so irrigation needs vary from year to year depending on the soil moisture deficit during the growing season. The main drivers of irrigation need are therefore rainfall and evapotranspiration.

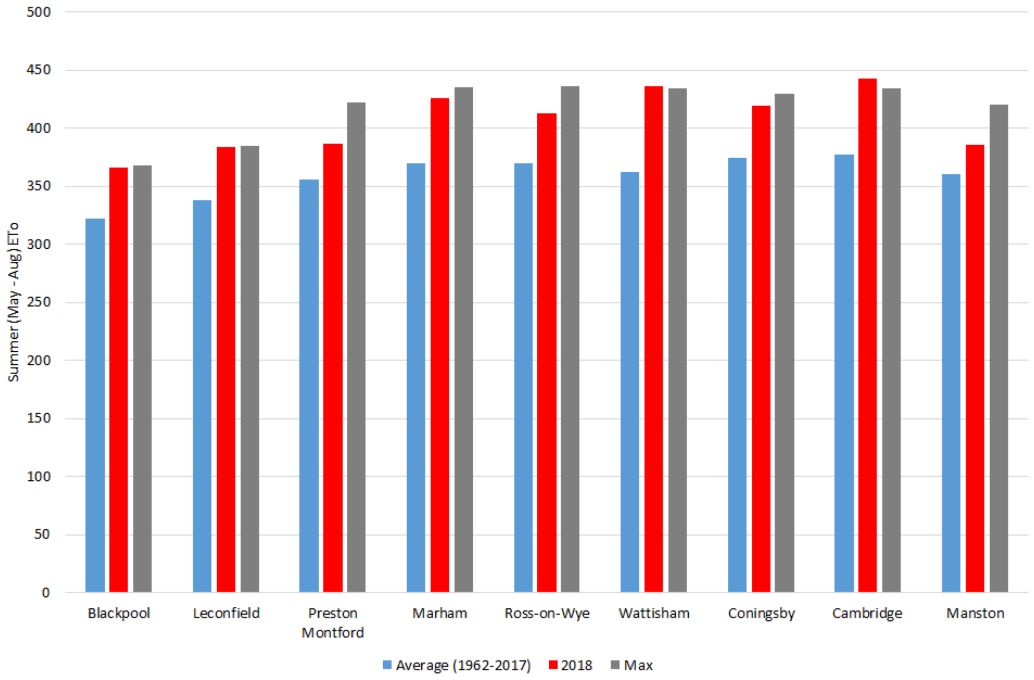
For each weather station an analysis of summer rainfall and ETo for 2018 was completed, for comparison against the long-term average climate. The results are summarised in Figure 2.

Figure 2 Mean summer (May to August) rainfall (a) and reference evapotranspiration (ETo) (b) for the reference weather stations based on 1962-2018. Values shown include the average (blue), 2018 (red) and minimum (for rainfall) or maximum (for ETo) (grey).

(a) Summer rainfall (mm) for 2018 for selected stations in England.



(b) Summer reference evapotranspiration (ETo, mm), for 2018 for selected stations in England.



For these sites summer (May to August) rainfall was, on average, only 63% of the long-term average (LTA) with a prolonged dry spell covering most of June and July. For reference evapotranspiration, on average ETo was 113% of LTA, with individual days exceeding 6 mm/d. This pattern of significantly reduced summer rainfall and high ET rates was broadly consistent across the country, and is the underlying reason why irrigation was so widely and intensively practised in 2018.

4.2 Agroclimatic indicator

For any given site and crop type, the irrigation water requirements for a crop depend on the daily balance between rainfall (P) and reference evapotranspiration (ETo) and the resultant fluctuations in soil moisture status. A useful variable that combines the interaction of these parameters is the potential soil moisture deficit (PSMD). Various previous studies (Knox et al., 1996; Rodriguez-Diaz et al., 2007; Knox et al., 2007) have shown a strong correlation between irrigation needs and the maximum value of PSMD in a season, and have therefore used $PSMD_{max}$ as an agroclimatic indicator. It is also extensively used in the OWU methodology.

The variable PSMD is calculated from:

$$PSMD_{i,j} = PSMD_{i-1,j} + ETo_{i,j} - P_{i,j}$$

Where

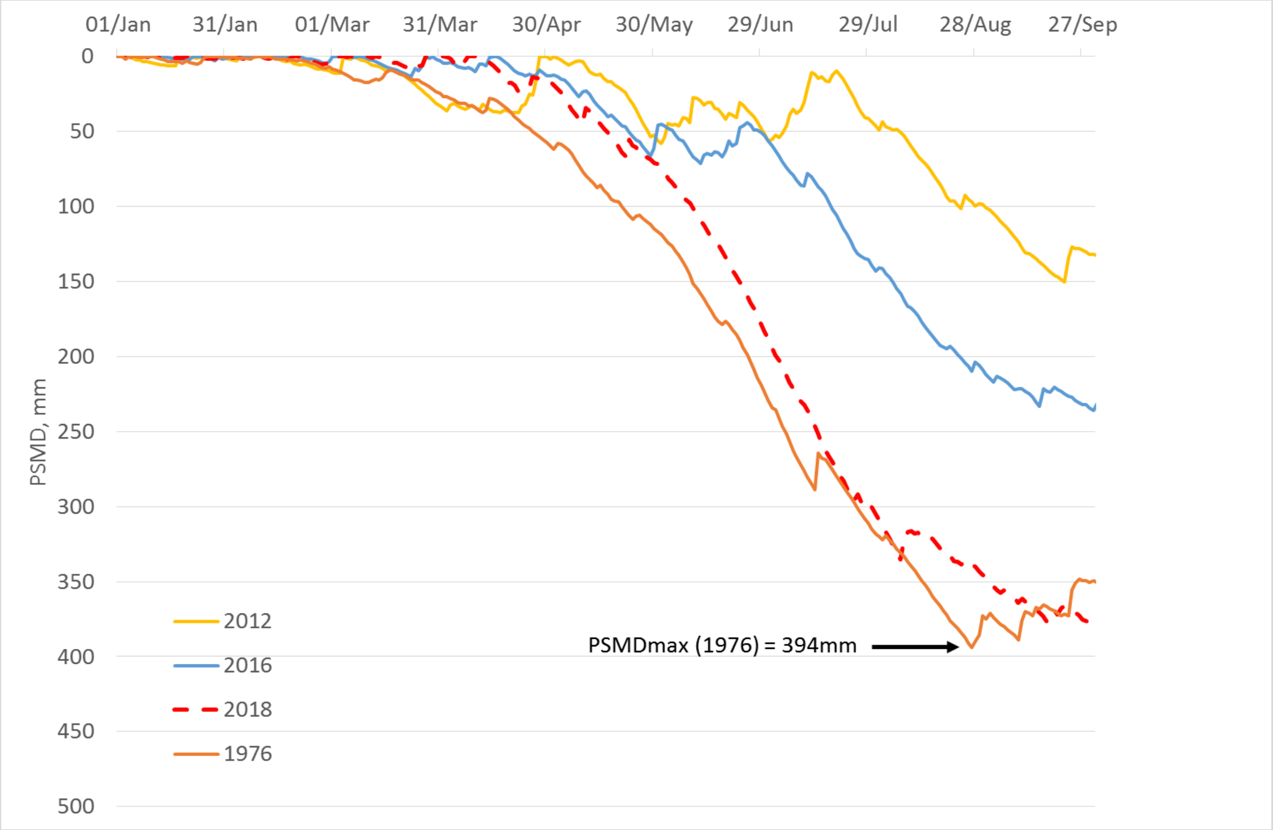
$PSMD_{i,j}$ = potential soil moisture deficit at the end of day i, in year j, mm
$ETo_{i,j}$ = potential evapotranspiration on day i, in year j, mm
$P_{i,j}$ = rainfall on day i, in year j, mm

On days where $P_{i,j} > (PSMD_{i-1,j} + ETo_{i,j})$ any initial soil moisture deficit is assumed to have been filled and $PSMD_{i,j} = 0$. In England, soil moisture deficits typically start to build up in early spring as ETo starts to exceed P, peak in mid-summer (July-August) and then decline through autumn and winter as P exceeds ETo. In England the excess of rainfall over ETo in winter means that PSMD is always replenished and the estimation of PSMD in each year can start with 1st January as day 1 and $PSMD_{1,j} = 0$.

The maximum value of $PSMD_{i,j}$ over the following 12 months is then the $PSMD_{max,j}$ for year j at that site.

An example of the temporal trend in PSMD for Cambridge is shown in Figure 3. A number of contrasting years are shown to highlight how the PSMD values vary between a typically ‘wet’ year (2012), an ‘average’ year (2016) and ‘extreme dry year (1976). Figure 3 also shows the PSMD data for 2018 and highlights how similar conditions were to 1976. Although the dry period started slightly later in 2018, the rising deficit was then at a rate very similar to 1976 with virtually no rain between 01 May and 30 July.

Figure 3 Potential soil moisture deficit (PSMD) for Cambridge for contrasting years. Data for 2018 shown in red.



4.3 Spatial comparison of agroclimate between 2018 and a 'design' dry year

The OWU methodology defines a 'design' dry year as the $\mathrm{PSMD_{max}}$ that is not exceeded in 80% of years (Weatherhead et al., 2002), that is, only 20 in 100 years (on average) would have a $\mathrm{PSMD_{max}}$ greater than the 'design' dry year. Figure 4 shows the average $\mathrm{PSMD_{max}}$ based on the long-term data record, together with $\mathrm{PSMD_{max}}$ values for the 'design' dry year, 2018, and the maximum value (1962-2018).

Figure 4 Estimated PSMD$_{max}$ for each weather station based on data for 1962 to 2018.

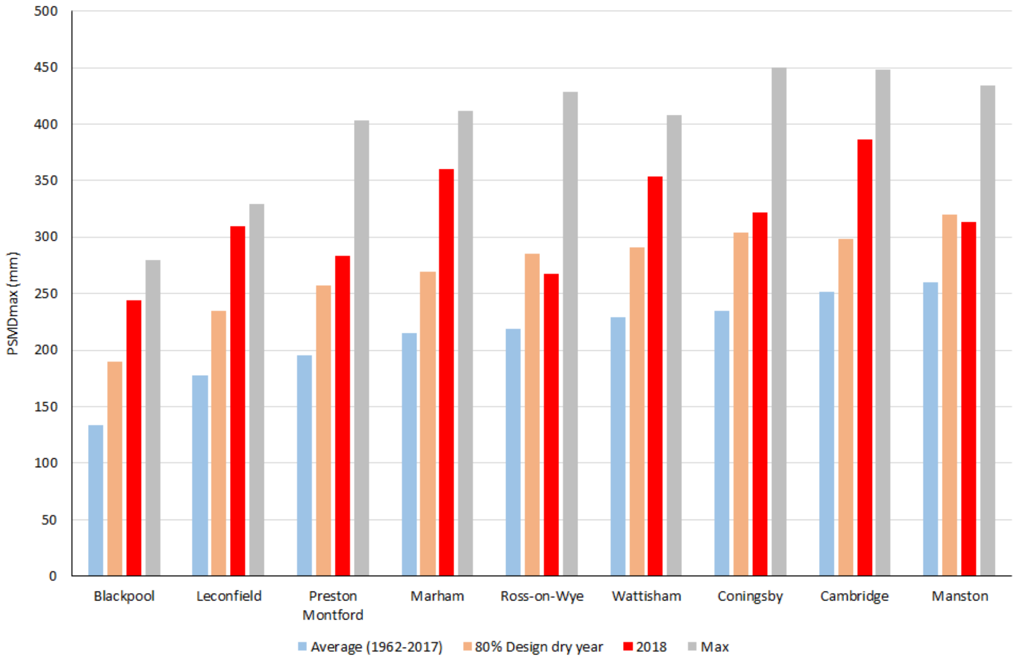


Figure 4 shows that 2018 was considerably drier than a 'design' dry year across most sites, except Manston. A detailed statistical analysis for each site is presented in Table 2. The final row shows how 2018 compares relative to a 'design' dry year; 2018 was clearly an extreme event. For most sites the estimated PSMD$_{max}$ values in the eastern region were in the top decile or <10% probability of exceedance compared to sites in western England, which were close to or below the 'design' dry year (74 to 88%)

Table 2 Statistical analysis of PSMD$_{max}$ for the reference weather stations.

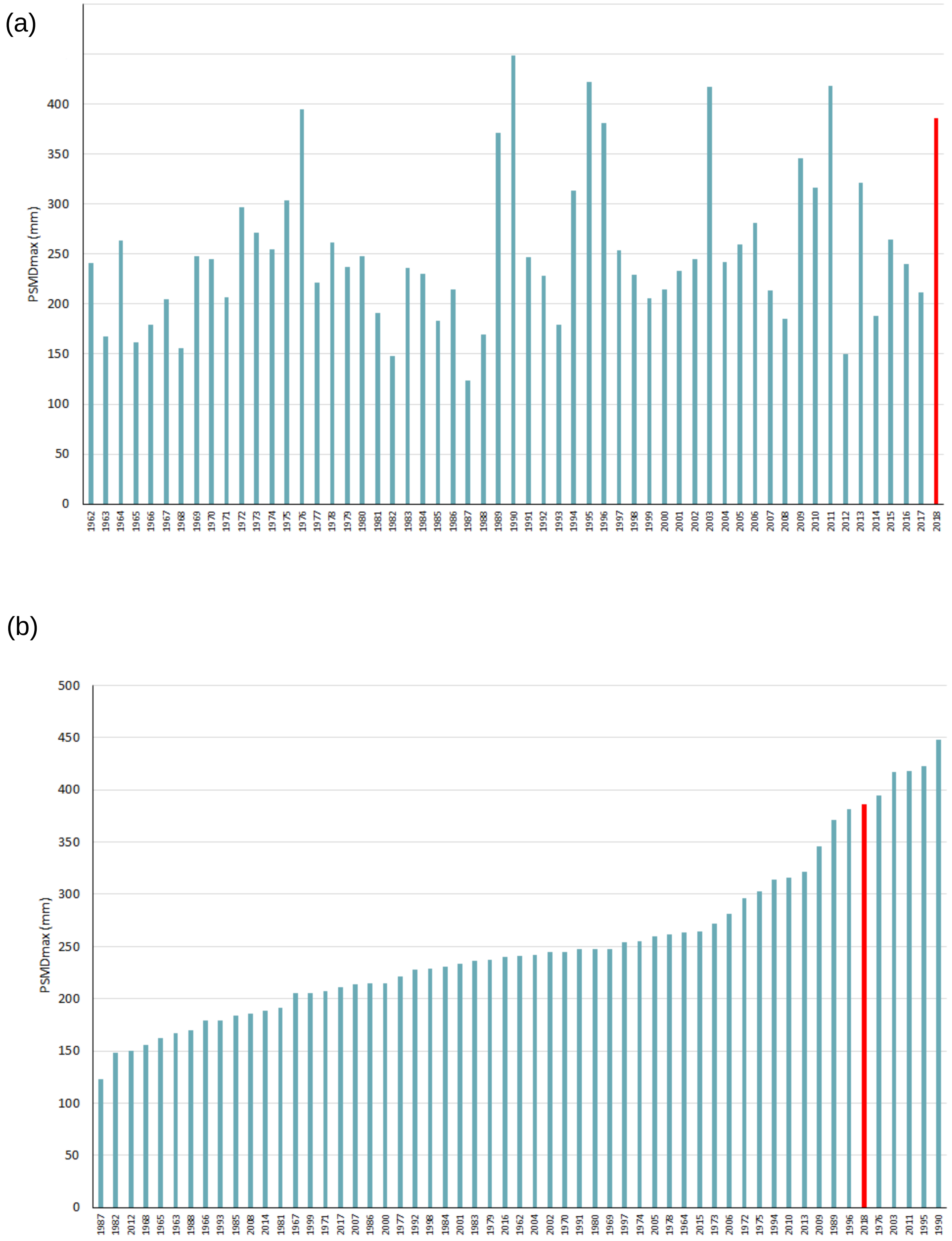
Variable	Blackpool	Leconfield	Preston Montford	Marham	Ross-on-Wye	Wattisham	Coningsby	Cambridge	Manston
Average PSMD$_{max}$, mm (1962 - 17)	134	177	196	215	219	229	234	251	260
2018 PSMD$_{max}$, mm	244	309	284	360	267	354	321	386	314
Max PSMD$_{max}$, mm	280	330	404	411	429	408	450	448	434
St Dev PSMD$_{max}$, mm	52.7	64.8	74.0	73.7	75.5	75.4	80.8	75.5	83.3
Probability of exceedance of 2018 PSMD$_{max}$ (62-91)	2%	2%	12%	2%	26%	5%	14%	4%	26%

From Table 2, we would expect the PSMD$_{max}$ in 2018 to be equalled or exceeded, in two years out of 100 at Blackpool, Leconfield and Marham; and at Cambridge and Wattisham ~five times.

4.4 Temporal analysis of agroclimate variability

The preceding analysis showed how the weather in 2018 varied spatially across England, relative to long-term conditions and a ‘design’ dry year. For a reference site (Cambridge) the analysis below shows the temporal variability. This is useful for identifying other similar drought years and to put 2018 in context with the historical record (Figure 5).

Figure 5 Temporal variability in PSMD$_{max}$ for Cambridge (1962 to 2018) (a) and ranked (b).

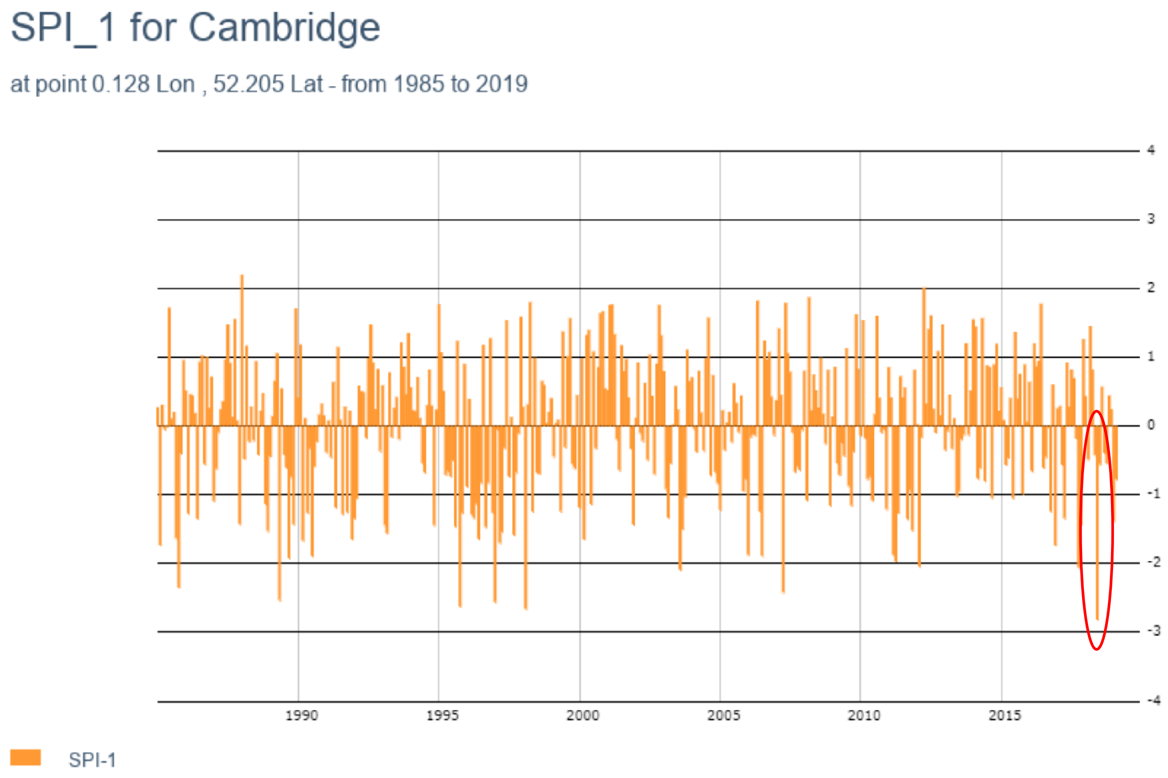


For Cambridge, 2018 had the 6th highest PSMD$_{max}$ in the record (1962 and 2018) ranked closely behind 1976. The more severe drought years included 2003, 2011 and 1990. The most extreme drought year was 1995 for this site.

In England the PSMD$_{max}$ has been widely used to support irrigation planning and water resource modelling, but it is not widely adopted internationally. Haro-Monteagudo et al. (2018) evaluated the utility of three well-established drought indices, including the standardised precipitation index (SPI), the standardised precipitation evapotranspiration index (SPEI) and the Palmer Drought Severity Index (PDSI), for use in England. In their analysis, the SPEI-3 drought indicator was found to be most suited to monitoring water availability and hence drought conditions for both rainfed and irrigated production.

Figure 6 shows, for example, the SPI_1 for Cambridge between 1985 and 2018. Values >-2 SPI are classified as being an “extreme drought”; in 2018 the SPI1 was close to -3.

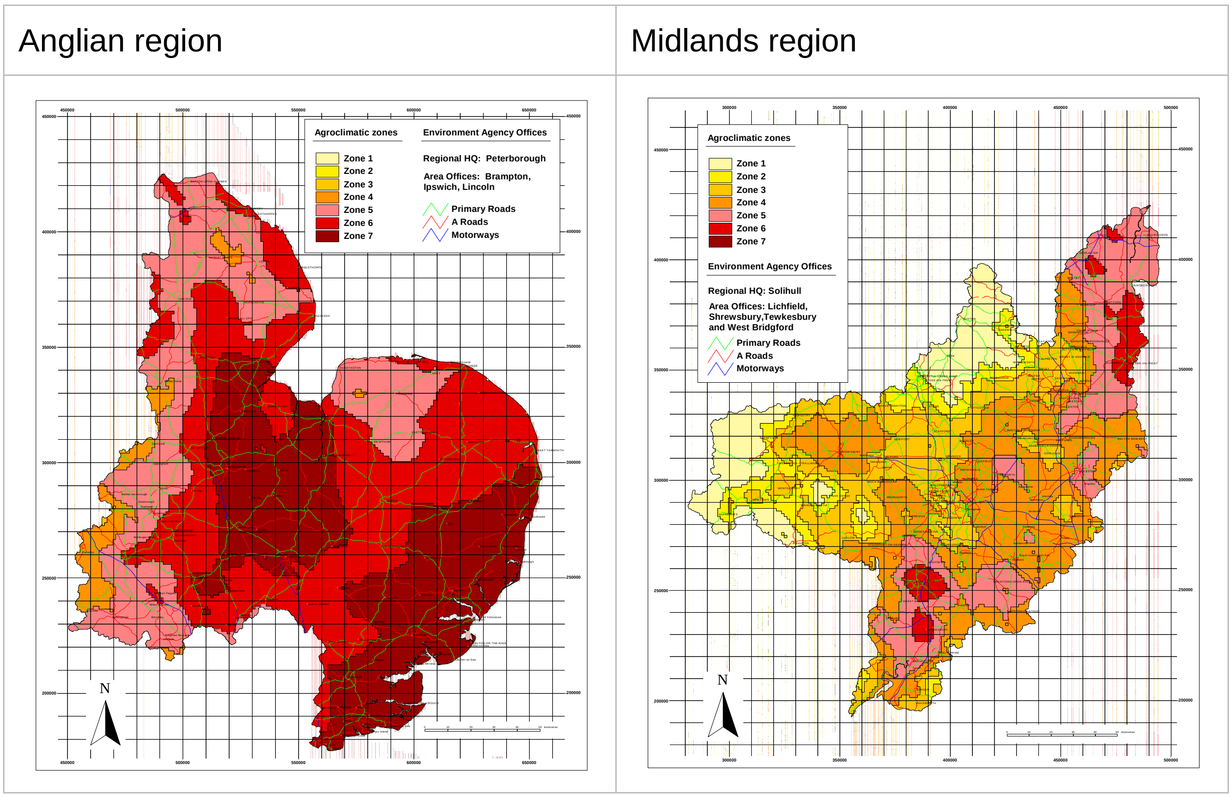
Figure 6 Mean Standardised Precipitation Index (SPI_1) for Cambridge for 1962 to 2018.



4.5 Optimum water use methodology agroclimate zones and irrigation needs

The approach embedded within the EA Optimum Water Use methodology (Weatherhead et al., 2002) for reviewing ‘reasonable’ needs and renewing spray irrigation abstraction licences relies on a set of defined agroclimatic zones (AgCl) which extend across England. These zones were originally modelled and mapped using a gridded climatology dataset of PSMD$_{max}$. Example agroclimate maps are shown in Figure 7.

Figure 7 Agroclimate maps for EA Anglian and Midlands regions (Weatherhead et al., 2002).


Anglian region

Midlands region

The OWU methodology also provides ‘look up’ tables on the irrigation needs (mm) for a range of crop types for a ‘design’ dry year. This enables the EA to estimate the volumetric demand (m^3) for a site based on the irrigation needs (mm) for a given crop and reported irrigated area (ha).The weather stations in this study spanned a number of agroclimate zones.

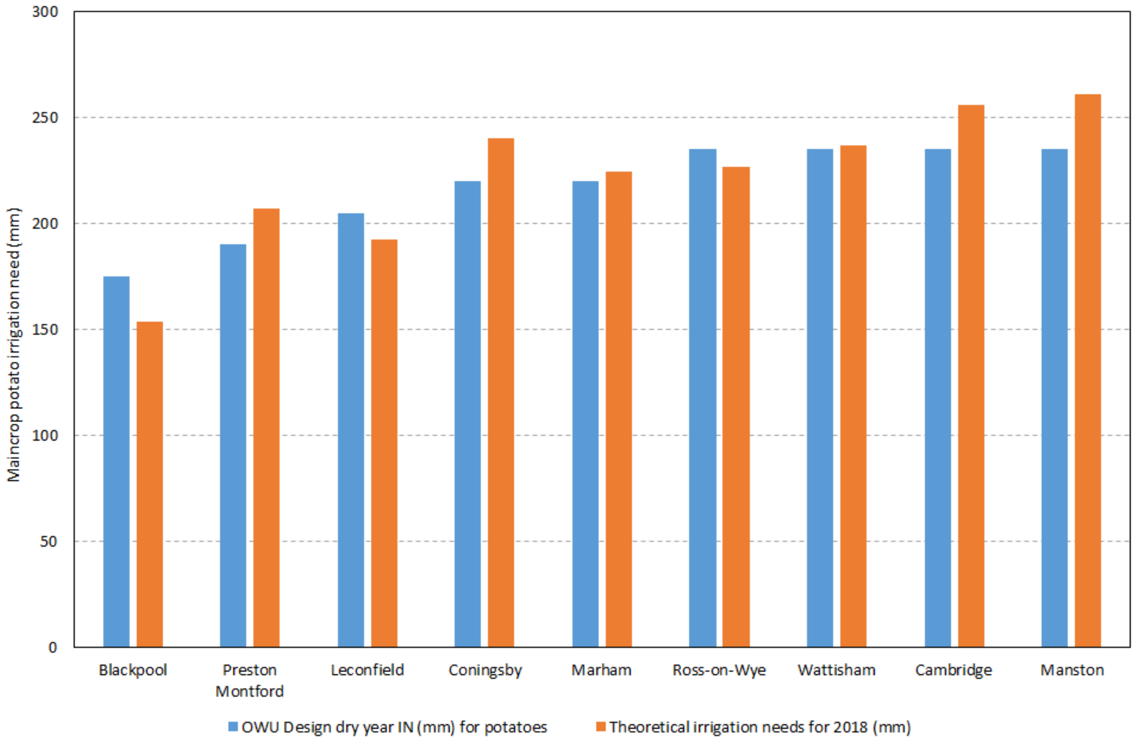
For each site, the estimated ‘design’ dry year irrigation needs (mm) for maincrop potatoes as reported in the OWU methodology were compared against the theoretical needs for 2018 (Table 3) estimated from the PSMD_{max}.

Table 3 Comparison of estimated ‘design’ dry year irrigation needs (mm) for maincrop potatoes as reported in the OWU methodology with theoretical needs for 2018 for each weather station.

Site	PSMDmax	AgCl zone	OWU ‘design’ dry year irrigation need (mm) for maincrop potatoes	Theoretical irrigation needs for maincrop potatoes in 2018 (mm)
Blackpool	135	3	175	154
Preston Montford	198	4	190	207
Leconfield	180	5	205	192
Coningsbry	236	6	220	240
Marham	218	6	220	225
Ross-on-Wye	220	7	235	227
Wattisham	232	7	235	237
Cambridge	254	7	235	256
Manston	260	7	235	261

Table 3 shows that the theoretical irrigation needs for maincrop potatoes in 2018 were higher than the ‘design’ dry needs for most sites in eastern and southern England, but close to, or marginally lower, for sites further west and north (Figure 8).

Figure 8 Comparison of OWU ‘design’ dry year irrigation needs for potatoes (mm) with estimated needs for 2018.



4.6 Grower reported irrigation needs and abstraction management in 2018

The preceding analyses focused on comparing the weather in 2018 to a ‘design’ dry year in both agroclimate (aridity) and irrigation need terms. This part of the study set out to gather information from selected growers on what actually happened in 2018.

Evidence was gathered via an email questionnaire distributed to approximately 30 growers spanning all major irrigated crop sectors coupled with a small number of one-to-one interviews, either by phone or face-to-face. The main issues emerging from the interviews are summarised below:

- High temperatures coupled with no rainfall for ~7 weeks put extreme pressure on the peak rates of abstraction (daily and monthly) as defined in growers’ abstraction licences;
- For many growers, the major constraint was actually irrigation infrastructure (water supply network on-farm) together with the lack of in-field application equipment. Many distribution systems were simply constrained by allowable flow rates which are a function of pipe sizing and pump capacity;
- Irrigation demand for maincrop potatoes (for scab control) coincided with high demands for other crop establishment most notably onions – this created serious challenges for prioritising irrigation on farms (irrigation intervals and application depths);

- There were also challenges reported linked to crop 'sacrificing' – and particularly the management decisions relating to whether businesses should partially irrigate all the irrigation command area or, instead, aim to fully irrigate a reduced area, with priority given to high-value crops where quality assurance was critical;
- Some growers reported trying to hire or buy additional irrigation equipment either locally or internationally, but there was no equipment on the domestic second-hand market and drought in the rest of Europe meant that there was no new irrigation stock available;
- Some lower value crops were irrigated simply 'to keep them going' during the drought conditions, with growers simply 'hoping it would rain';
- One grower reported that "It was like being in a lifeboat and not knowing how many days you had to survive with a limited amount of water";
- Many growers used all their licensed amount and tried to obtain additional water (for example, through trading or re-instating existing 'sleeping' licences) where possible;
- The EA showed some flexibility, but in many cases this was too late. Similarly, retailers relaxed specifications, but again, for many it was too late, and;
- There were reported to be some inconsistencies between regions in the way the EA had managed the emerging drought situation and specifically in how they dealt with farmer concerns; equally, there was very high praise for some regional offices who were acknowledged as being particularly supportive to growers

The email questions focused on irrigation depths and whether individual growers target (scheduled) applications were achieved or constrained by system or abstraction restrictions during 2018. Only a small sample of growers responded (7) to the email; their anonymised responses are given in Table 4.

Table 4 Grower reported typical actual irrigation applications (depths applied, mm) in 2018 on maincrop potatoes.

Farmer	County	Agroclimate zone	'Design' dry year irrigation need (mm)	Reported total irrigation application (mm)
1	N Norfolk	6	220	250 No constraints
2	Norfolk	5	205	120 to 130mm on salad potatoes
3	Norfolk	6	220	275 No constraints
4	N Norfolk	6	220	200
5	Suffolk	7	235	300
6	S Lincs	5	205	230
7	N Norfolk	6	220	265

The general message emerging from this informal assessment of a small sample of growers was that the actual irrigation applications applied during 2018 were close to or in excess of the 'design' dry year needs for those locations. Previous analyses highlighted that 2018 was well in excess of a 'design' dry year in agroclimate terms; this feedback from growers reinforces that assessment.

It is also worth recognising the differences between net and gross irrigation needs. The modelled irrigation needs in the OWU methodology represent net irrigation requirements, whereas the figures reported by growers would be gross requirements, where some allowance might have been made for conveyance losses and in-field inefficiencies. Since most potato irrigation in the UK is from mobile overhead systems supplied via underground pipes, the conveyance losses are typically relatively small. The in-field efficiencies should reflect the values normally assumed when planning system capacities and scheduling irrigation, and are not necessarily the same as the efficiencies actually achieved. In contrast to international procedures, UK farmers typically ignore in-field losses and non-uniformity when scheduling, implicitly accepting some under-irrigation. Under this assumption, gross and net in-field irrigation demands are the same. However, with increased emphasis on potato quality and the use of soil moisture based scheduling techniques, this is likely to lead to full irrigation and hence higher gross demands in the future.

5. Optimum Water Use methodology: potential areas requiring revision

The Optimum Water Use methodology to determine the optimum or ‘reasonable’ dry year irrigation water requirements for a range of outdoor crops in England and Wales was developed by the EA following three phases of development. The Best Practice Guidelines and supporting Technical Report to support the review and assessment of abstraction licences as part of the CAMS process was finally implemented in 2002. No revisions or developments have been implemented since that work was completed. The purpose of this part of the study was to therefore briefly consider what changes might be needed, taking into account any lessons learnt from 2018 and more fundamental changes in agricultural and horticultural irrigation over the last decade. The suggested areas which warrant further attention in the Optimum Water Use methodology are briefly summarised below (Table 5).

Table 5 Suggested areas for methodological improvement in existing Optimum Water Use methodology.

Agricultural sub sector	Description
Trickle (drip) irrigation	The use of trickle or drip irrigation has increased steadily over the last decade, with its use now much more widespread on outdoor field-scale high-value crops. Previously, its adoption was limited to small scale enterprises. There is a need to consider how the existing Optimum Water Use determination methodology takes trickle irrigation use into account, particularly in relation to applicant reported areas irrigated. With trickle irrigation only a proportion of the total field area is ever wetted, depending on crop type, the planting configuration and local soil characteristics. This is in contrast to most overhead systems which are designed to wet the entire field. Trickle irrigation can therefore satisfy the crop water requirements without an unnecessary amount of water being applied to bare ground. A report was produced for the EA (Knox et al., 2003) to highlight these nuances but awareness of it is likely to be low within current EA

	abstraction staff. Specifically, a set of ground cover reduction factors were proposed to assist Agency staff in assessing the impact that different cropped areas might have on trickle irrigation water use, and hence 'reasonable' irrigation demand. Its relevance is also particularly important in the context of dealing with many new authorisations for trickle in 2020.
Soft fruit production (strawberries)	Strawberry production in England was originally outdoors and soil-based, with fumigation used to sterilise the soil each year. All commercial strawberry production is now under cover (protected) using polytunnels structures and due to increased costs for labour and harvest; systems have thus migrated from the soil into raised 'table top' and soil less systems (coir based). Irrigation management has also changed dramatically, with closed loop systems incorporating fertigation. In a recent benchmarking study on the economics of strawberry irrigation, Morris et al (2017) reported that mean irrigation water use for a sample of UK growers was about 83mm, 99mm and 176 mm, for 60-day,main-season and everbearer strawberries, respectively, although there was considerable variation about these means. The optimum irrigation needs reported in OWU are no longer relevant for current production systems and should be completely revised to reflect these changes.
Soft fruit production (other crops)	The UK soft fruit sector has expanded significantly over the last decade both in terms of production (area), productivity (yield) and diversity (range of crops). The existing Optimum Water Use methodology currently only includes strawberries, raspberries and blackberries (the latter two crop types also having experienced dramatic crop husbandry changes). Further work is required to understand the irrigation needs for soft fruit crops including raspberries, blackberries, blackcurrants and blueberries, which are increasingly being grown in response to 'super fruit' consumer and market demands.
Niche crops (herbs)	High-value herb production and speciality vegetables are not currently included in the existing Optimum Water Use methodology. In 2002 these were minor crop sectors. Although their cropped areas are still small, their critical dependence on irrigation for quality assurance and their high value, warrant further work to quantify their irrigation needs. Data on indicative water use for this sector should be available from industry sources or key informants.
Salads and ready to eat (RTE) vegetables	The existing Optimum Water Use methodology only included lettuce and salad onions. However, the UK leafy salads industry has expanded and diversified enormously. There are now many different types of lettuce and a variety of baby leaf or ready to eat (RTE) salad vegetables (e.g. radish) being grown, mainly in the Fens, south coast (Hampshire) and West Midlands. The new methods of cultivation with many now being multiple cropped (2 or 3 crops per season) coupled with major changes in the way the crops are managed and irrigated,

	warrants further work to revise existing estimates of irrigation need for the 'lettuces' category in Optimum Water Use.
Energy crops	Most energy crops including maize are not typically irrigated, but given the rapid expansion of anaerobic digestion plants and the experiences of 2018 on crop yields, it would be worth investigating whether maize crops in the UK are receiving any supplemental irrigation, and if so, the typical application requirements. This is likely to be a minority crop sector but one that should still be considered given the steady increase in cropped area (UK maize production has increased from 44,000 ha in 1991 to 194,000 ha in 2016).

6. Abstractor guidance: planning for future drought events

The final stage focused on how spray irrigation abstractors might better plan and manage against future extreme droughts and their impacts, taking into account that seeking new abstraction licences and/or additional licensed quantities on existing licences in most catchments is no longer a viable option. Businesses therefore need to consider innovative alternatives including identifying alternative water resources, implementing strategies to improve water efficiency to reduce non-beneficial losses through investment in better scheduling and precision irrigation, and promoting more collaborative approaches to local water management through, for example, sharing/trading water within water abstractor groups.

Recent research by Rey et al. (2017) into droughts and their impacts on the UK agricultural sector has also highlighted the importance of adopting a vertically integrated drought management approach coupled with developing a better understanding of past drought impacts and management options to improve future decision-making during drought events. The guidance presented here draws heavily on that evidence to provide new guidance to support Spray Irrigation abstractors in preparing for future drought events.

Different types of drought management action based on the spatial scale and time frame can be distinguished. These actions range from farm-scale responses to catchment-scale actions. In relation to time scale, we can differentiate between short-term coping strategies that adapt farm activities to water availability at a point in time within a drought; and longer-term strategic business developments designed to manage future drought risks and increase resilience.

Short-term coping strategies (farm level)

During a drought, there are various on-farm strategies that can be applied in order to reduce the economic impact and help farm business to meet their contractual obligations (if any). These can be broadly classified into three groups:

(1) Strategies aimed at making best use of available water relative to their own water resource position and infrastructure constraints;

(2) Liaising with the water regulator (directly or indirectly) to either reduce the likelihood of abstraction restrictions and/or to obtain maximum warning and support from them, and;

(3) Implementing additional coping strategies such as water trades or renegotiating existing contracts.

Rey et al. (2017) also asked farmers to identify their two most favoured strategies. They choose (i) working collectively through a local water abstractors group (WAG) to negotiate with the water regulator (EA) and (ii) developing a drought management plan. A summary of the main short-term coping strategies identified by Rey et al. (2017) for SI abstractors is given in Table 6.

Table 6 Characteristics of the main short-term coping strategies applied by UK farmers in response to drought and abstraction restrictions (Source: Rey et al., 2017).

Coping strategy	Description	Limitations
Evaluate water resource position	To assess how much water is available for the crops and then make a decision about how best to proceed	
Crop prioritization	To prioritize certain crops or varieties based on their drought-tolerance and/or economic value	Not suitable for farmers that focus their irrigated production on one main crop
Irrigate reduced area to the full schedule	If there is not enough water to irrigate all the crops, the farmer will only irrigate a certain area/crop based on priorities	This can lead to substantial yield and quality impacts on the remaining crop area
Irrigate full area to a reduced schedule	If there is not enough water to irrigate all the crops, the farmer will irrigate all the crops although the water requirements would be not fully met	Could affect quality, so less suitable for high-value crops (potatoes, vegetables) subject to forward contract commitments
Irrigate at night	Only irrigate at night to reduce ET losses	Irrigation infrastructure could be insufficient to irrigate the full crop area during night hours
Water trading	To trade water with other water abstractors, to obtain extra water during water shortage periods	Administrative licensing process is not straightforward or quick. Several barriers to trade. It needs the approval of the EA

Longer-term strategic planning

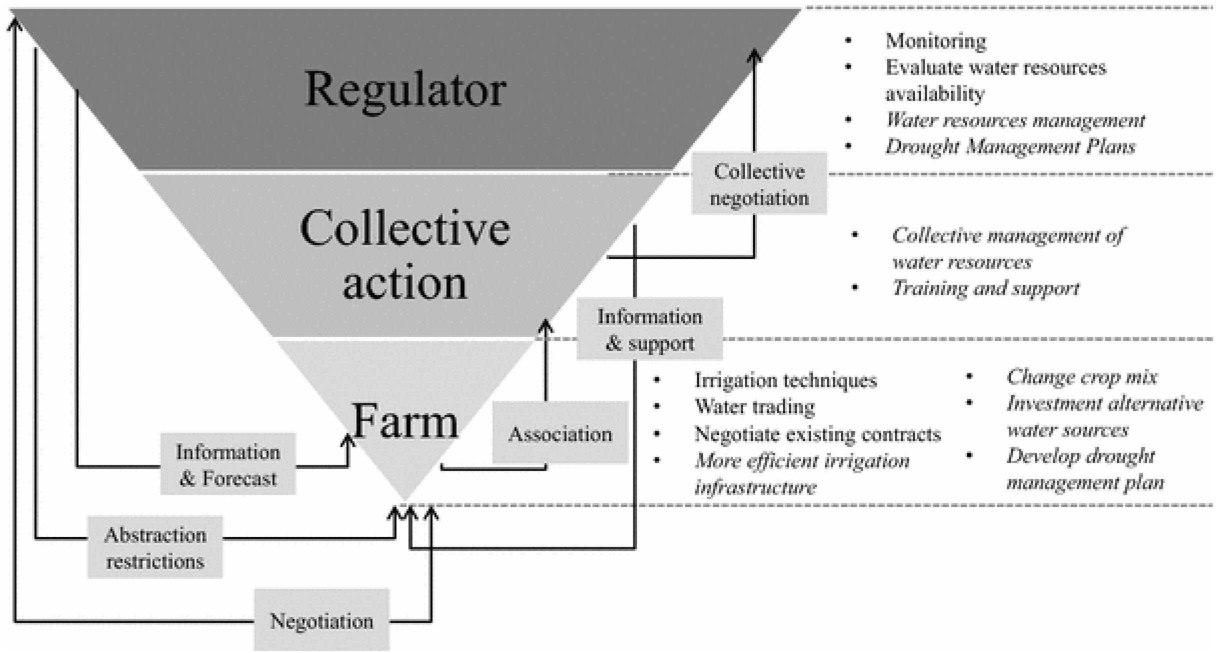
After being affected by past drought events, Rey et al. (2017) reported that most of the farmers surveyed made more substantive changes in their businesses to increase their resilience to future droughts. The main options undertaken included:

- Development of a drought management plan to establish a protocol for the business in the event of drought;
- Investment in alternative water resources and more efficient irrigation infrastructure. This includes long-term investments to secure water supply (e.g. reservoir construction, multiple abstraction sources, rainwater harvesting), on-

farm distribution networks and switching to more efficient irrigation application technologies;
- Modifying crop selection and planting programmes to grow more drought-tolerant or less water-intensive varieties, and;
- Other strategies such as improving soil management to increase water retention, and adopting collective action through farmer associations such as water abstractor groups or producer organisations.

In summary, research by Rey et al. (2017) has shown how UK farmers have adapted their businesses and become more resilient to drought than they were some decades ago, despite increasing water scarcity (Figure 9). This has arisen primarily through investments in alternative water sources, improved farm drought planning, and collective farmer action. Improved working relationships with the EA during drought has also been a critical factor. The EA's approach to managing drought has also evolved over time, changing to a more proactive attitude, recognising the importance of irrigators being involved in drought management decisions and providing better forecast information to guide farm-level decisions.

Figure 9 Main drought management actors and actions related to agriculture at different spatial scales (strategic planning activities shown in italics) (Source: Rey at al., 2017).



Assessing future drought risks to inform business planning (D-Risk)

Finally, another useful source of information for growers to better understand the impacts of future drought would be through application of the D-Risk webtool. This free online tool (www.d-risk.eu) was co-designed and developed with growers to help farm businesses understand their complex abstraction and drought-related risks and to support informed decision making regarding crop planning and on-farm water resources infrastructure investment.

The D-Risk webtool enables farmers to understand their current or 'baseline' level of drought risk and then to conduct various 'what if' analyses to assess the consequences of business adaptation to drought risk. These include, for example, evaluating the consequences of reducing their overall irrigated area, modifying planting programmes and crop mix (changing the agronomic need for irrigation in a dry year), changing irrigation schedules (prioritising which crops should be irrigated) or investing in on-farm reservoir storage (to increase total resource availability and reliability and/or support business expansion plans).

Many farmers are also acutely aware that their current annual licensed allocation and 'headroom' are at risk as the government implement major legislative reforms to the abstraction licensing regime to reduce levels of over-abstraction and restore environmental flows. The D-Risk tool can also support farm businesses in understanding how potential reductions in licensed allocation and 'headroom' might impact on their future cropping programmes. Example case study applications are provided on the D-Risk website (http://www.d-risk.eu/index.php?params=casestudies).

Evidence from the 2018 drought has certainly highlighted the importance of a vertically integrated management approach in helping to reduce the impacts of drought at the farm level.

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The 2018 met data is Met Office Crown copyright, the historical data is homogenised Met Office data using the JBA (2018) methodology, all supplied under licence to Cranfield University.

7. References

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8. Appendix

8.1 Missing data for weather stations

Station ID 370, Leconfield (53.8744°N, -0.44009°E)

Station ID 393, Coningsby (53.0935°N, -0.17119°E)
- Wind speed from Cranwell (1962 – 2018)

Station ID 409, Marham (52.6510°N, 0.56772°E)

Station ID 440, Wattisham (52.1234°N, 0.95910°E)

Station ID 455, Cambridge (52.2450°N, 0.10196°E)
- Wind speed from Bedford (1962 – 2018)

Station ID 638, Preston Montford (52.7243°N, -2.84043°E)
- Wind speed from Shawbury (1962 – 2018)
- Air and dewpoint temperatures from Edge (2016 – 2018)

Station ID 671, Ross-on-Wye (51.9108°N, -2.58441°E)
- Wind speed from Pershore (1962 – 2018)

Station ID 775, Manston (51.3460°N, 1.33716°E)
- Sunshine from Wye (1962 – 2015)
- Air temperature from Faversham (2018)

Station ID 1090, Blackpool (53.7746°N, -3.03647°E)

8.2 Reference evapotranspiration (ETo) estimation

Reference evapotranspiration (ETo) was estimated using the Penman-Monteith equation as described by the Food and Agriculture Organisation of the United Nations (FAO) using factors for a grass reference crop (Allen et al., 1998).

As data on sunshine were not available for all stations, incoming solar radiation was estimated from sunshine for Wattisham, Cambridge, Preston Montford, Manston, Ross-on-Wye and Blackpool using:

$$R_s = R_a\left(a_s + b_s \tfrac{n}{N}\right)$$

Where:

Ra	extra-terrestrial radiation, MJ m^{-2} d^{-1}
Rs	incoming shortwave radiation, MJ m^{-2} d^{-1}
as	Ångström constant
bs	Ångström constant
n	sunshine hours, h d^{-1}
N	maximum daylight hours, h d^{-1}

These were then used to calibrate the constant, *a,* in the Hargreaves equation for incoming solar radiation:

$$R_s = a\, R_a (T_{max} - T_{min})^{0.5}$$

Where:

T_{max} and T_{min} are maximum and minimum air temperature, respectively.

The Hargreaves equation was then used for all stations and years.

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Knox, Jerry W.

2019-04-25

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