Task 2 Agricultural water demand forecasts: Baseline demand (Part I)

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Table of Contents

1. BACKGROUND 4

2. STUDY AIM AND OBJECTIVES 4

3. MAPPING EA CAMS CATCHMENTS IN THE WRE REGION 5

4. METHODOLOGY 7

4.1 LICENSED AGRICULTURAL ABSTRACTION IN THE WRE REGION 7
4.2 MODELLING BASELINE (UNCONSTRAINED) AGRICULTURAL IRRIGATION DEMAND 11
4.3 IRRIGATION DEMAND ESTIMATION TOOLBOX FOR WRE SIMULATOR 15

5. MODELLING OUTPUTS 16

5.1 CORRELATING IRRIGATION DEMAND, AGROCLIMATE AND ABSTRACTION 16
5.2 AGRICULTURAL DEMAND ESTIMATION: EXAMPLE APPLICATION 17

6. REFERENCES 23

List of Figures

Figure 1 Spatial extent of CAMS catchments included in the WRE region. 5
Figure 2 Primary and secondary NALD categories, including purpose and source. 7
Figure 3 Spatial distribution of licensed intensity (Ml/ha) for agriculture in the WRE region. 9
Figure 4 Monthly timing of spray irrigation demand (Ml/day) in the WRE region based on 2010. Error bars show the reported inter-annual variation between 2005 and 2010 (Source: Knox et al., 2015). 10
Figure 5 Timing of water abstraction for storage, expressed a proportion of total abstraction for storage, based on EA NALD data for 2000 to 2006. Error bars show the maximum variation over the period (Source: Weatherhead et al., 2008). 10
Figure 6 Schematic flowchart to estimate theoretical annual theoretical irrigation demand (unconstrained), by CAMS catchment. 12
Figure 7 Soil type (left panel) and available water content (right panel) in the WRE region. 14
Figure 8 Components of the irrigation demand estimation toolbox for the WRE simulator. 15
Figure 9 Schematic showing the agricultural irrigation demand estimation toolbox. 15
Figure 10 Linear correlations between irrigation demand (Ml/year) estimated with WaSim and reported irrigation demand for each CAMS catchment in the WRE region. 17
Figure 11 Graphical representation of data included in the irrigation demand estimation toolbox, for the Cam and Ely Ouse catchment. 18
Figure 12 Estimating theoretical volumetric annual agricultural demand based on agroclimate. 19
Figure 13 Estimated split in demand from surface and groundwater. 19
Figure 14 Monthly distribution of surface and groundwater irrigation demand. 19

List of Tables

Table 1 EA CAMS catchments and their area included within the WRE region. 6
Table 2 Average licensed volume (Ml) for general agriculture, by catchment in the WRE region. 8
Table 3 Cropped areas (ha) and percentage irrigated in WRE region................................. 13
Table 4 Cropped and irrigated areas per CAMS within WRE region. The areas have been weighted according to the percentage of surface within WRE considering an even distribution... 13
Table 5 Squared Pearson correlation coefficient between modelled irrigation demand and agroclimate and Mean Squared Error (MSE) between modelled irrigation demand and reported abstractions, by CAMS catchment in the WRE region. 16
Table 6 Linear regression components for irrigation demand estimation. 20
Table 7 Monthly surface water demand distribution, by CAMS catchment.......................... 21
Table 8 Monthly groundwater demand distribution, by CAMS catchment. 22

Abbreviations

AW: Anglian Water
CAMS: Catchment Abstraction Management Strategy
EA: Environment Agency
NALD: National Abstraction License Database
PSMD: Potential Soil Moisture Deficit
RDM: Robust Decision Making
WRE: Water Resources East
WRMP: Water Resources Management Plan
WRZ: Water Resources Zone

1. Background

The Anglian Water WRE project has adopted a robust decision-making (RDM) approach to evaluate a range of future water resource planning strategies and to identify those that would be robust under a range of plausible futures. The evaluation includes the use of multiple metrics to assess system resilience and performance and to inform stakeholder engagement. The RDM evaluations will be undertaken using a regional water resource simulator, being developed by the University of Manchester and Atkins. This model represents all the water resource zones (WRZ) in the Anglian Water WRE region, including the sources of supply and centres of demand, as well as proposed new supply schemes. The simulator will be capable of evaluating multiple alternate system designs under a range of future scenario. In order to analyse future planning strategies that include agriculture as a specific sector, it will be necessary to modify the simulator, to include agricultural nodes and demands for irrigated agriculture operating under a range of contrasting agroclimatic and socio-economic scenario.

Cranfield University was appointed to lead the agricultural demand components in WRE. A previous scoping study by Knox et al. (2016) conducted a preliminary assessment of the agricultural sector within the WRE region to understand the nature and composition of water use in the sector, the drivers likely to impact on future demand and the opportunities for stakeholder engagement and collaboration with the farming community. The study highlighted that significant importance and economic value that agriculture contributes to the rural economy and landscape in the region, its dependence on water for supporting production of high-value cropping and the ‘hotspot’ catchments where future imbalances between agricultural supply and demand were likely to occur.

2. Study aim and objectives

The agricultural component of WRE includes 5 specific tasks. This report focuses on Task II ‘Agricultural water demand forecasts’. Task II comprises of two parts, a baseline agricultural water demand (Part I) and future agricultural demand (Part II). This report deals with Part I (only). Task I focuses on developing a set of agricultural narratives, which will ultimately be used to inform the framing and boundary conditions for the future agricultural demand forecasts (Task II, Part II). This work for Task I is currently underway. The overall aim of Task II was to develop a series of algorithms to estimate the spatial and temporal changes in agricultural water demand (baseline and future) taking into account changing agronomic and agroclimatic conditions, and agro-economic and socio-economic uncertainty.

For irrigated cropping, agricultural demand depends on the area of each crop grown (ha), the proportion of each crop that is irrigated (%) and the depths of water applied (mm). Each of these in turn depends on a range of agro-economic and technical conditions, as well as the fundamental agronomic and agroclimatic conditions, which will themselves vary, depending on summer weather conditions. Irrigation demand can therefore vary significantly from month and month and from year to year depending on the relative mix of these underlying conditions.

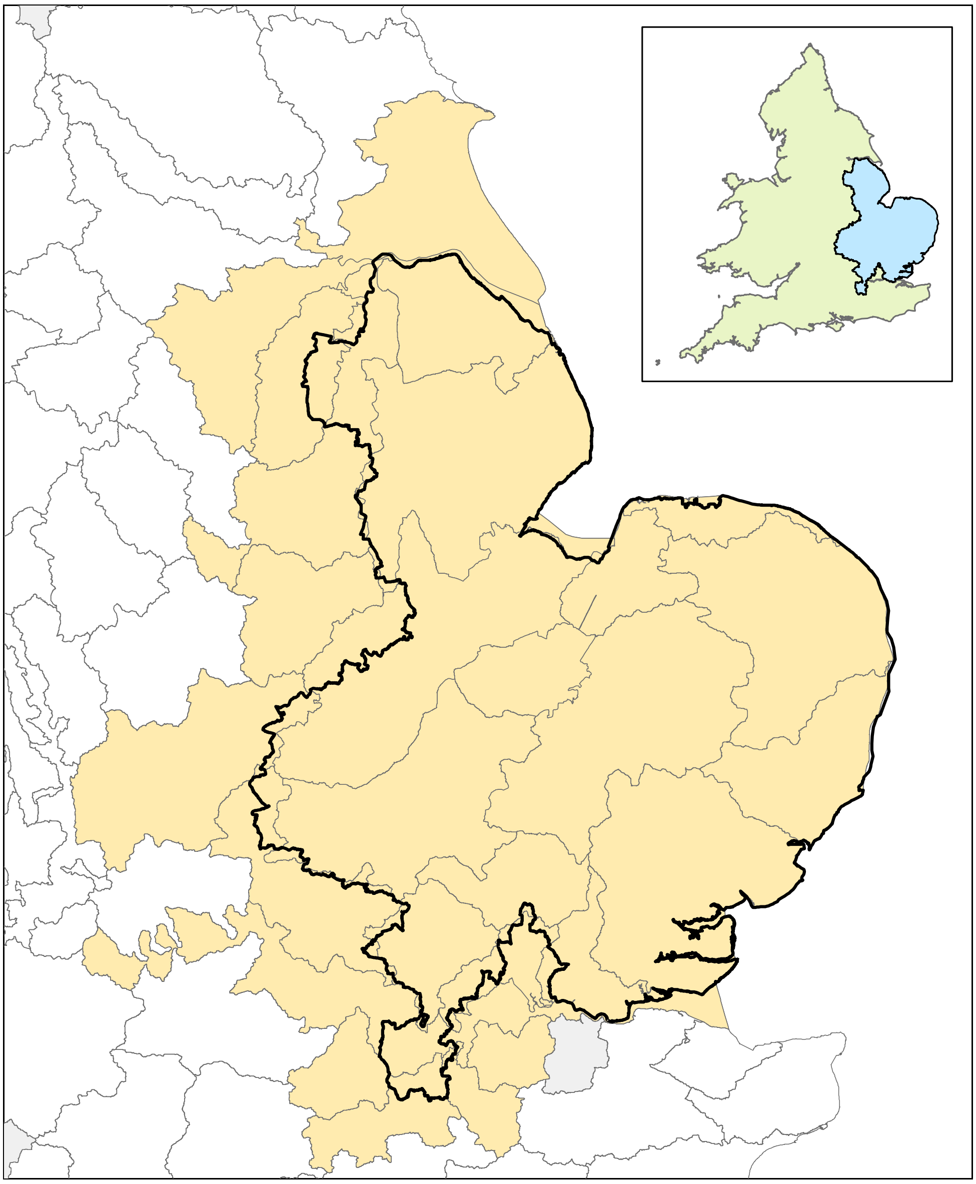
The output from Task II (Part I) includes this technical report and a geospatial database containing information to derive baseline agricultural irrigation water demand, aggregated by EA CAMS catchment, and split according to water source (surface and ground water). A separate supporting technical report (due to be completed end Jan 2017) will contain the equivalent algorithms and datasets to derive likely changes in future agricultural water demand. All water demands for irrigated agriculture reported in both Part I and II reports are expressed as Ml/d. Modelling has been conducted at the EA CAMS catchment level for alignment with the WRZ and nodes in the WRE simulator, and split according their source (surface or groundwater).

This report explicitly focuses on establishing the algorithms and supporting database to estimate baseline (current) agricultural irrigation demand (Part I). Existing published data derived from the EA National Abstraction Licence Database (NALD) has been used to assess historic patterns in demand (monthly), the relative split between surface and groundwater abstraction, and to validate modelled (theoretical) baseline demands. These data are not included in this report. A brief outline of the methodology that has been developed, including the algorithms and the database to support baseline demand are provided below.

3. Mapping EA CAMS catchments in the WRE region

For agricultural demand forecasting, it is appropriate to consider the spatial distribution of irrigation demand and abstractions at a catchment scale. The WRE region spans 24 water resource zones (WRZ) which overlap with 26 EA CAMS catchments across five EA regions. The WRE area includes the East of England, approximately half of East Midlands, and small portions of the South East, London, Yorkshire and Humber (Figure 1).

Figure 1 Spatial extent of CAMS catchments included in the WRE region.



Five catchments including the Don and Rother, Hull and East Riding, Loddon, London and Soar each have less than 1% of their area located within the WRE region. Collectively, they account for a very small proportion of the total licensed and actual abstraction volumes for agriculture in the WRE region and have therefore been excluded from subsequent analysis. Table 1 summarises extent and proportion of the remaining 21 catchments within the WRE region. Five large CAMS catchments including the Witham, Cam and Ely Ouse, Combined Essex, Welland and Nene, and Broadland Rivers account for over half the total WRE region.

Table 1 EA CAMS catchments and their area included within the WRE region.

EA CAMS catchment	EA Region	Area (ha)	Propn (%) within WRE	Propn (%)of WRE region
Witham, Steeping, Great Eau, Long Eau	Anglian	398,274	94.71	12.24
Cam and Ely Ouse (incl South Level)	Anglian	366,603	100.00	11.90
Combined Essex	Anglian	353,073	98.07	11.24
Welland and Nene	Anglian	397,018	86.39	11.13
Broadland Rivers	Anglian	318,390	99.98	10.33
Upper and Bedford Ouse	Anglian	304,704	98.48	9.74
East Suffolk	Anglian	163,090	99.76	5.28
Louth, Grimsby and Ancholme	Anglian	162,803	89.69	4.74
Upper Lee	South East	104,849	98.78	3.36
North West Norfolk	Anglian	96,654	98.88	3.10
Colne	South East	102,120	93.00	3.08
Old Bedford (incl Middle Level)	Anglian	92,230	100.00	2.99
Roding, Beam and Ingrebourne	South East	75,937	89.55	2.21
Lower Trent and Erewash	Midlands	241,368	26.56	2.08
North Norfolk	Anglian	54,553	93.20	1.65
Thames Corridor	South East	261,016	11.73	0.99
Cherwell, Thame and Wye	South East	172,035	16.57	0.93
Idle and Torne	Midlands	127,091	20.36	0.84
Wey	South East	89,037	17.75	0.51
Warwickshire Avon	Midlands	278,807	5.30	0.48
Mole	South East	47,614	3.55	0.05
Total		**3,046,699**		**98.89**

Given that the agricultural demand forecasts (both baseline and future) are aggregated to the EA CAMS catchment level, it will be necessary to consider in the WRE simulator how the spatial distribution of agricultural demand (catchment level) relate to specific points (nodes) in the WRE simulator. It may be necessary to split some of the larger CAMS (e.g. Cam and Ely Ouse) into sub-catchment units to provide an appropriate level of resolution for modelling and analysing the multi-sector resource options.

4. Methodology

The methodology adopted in Task II (Part I) involved 3 stages:

(i) Analysis of existing published data originally derived from EA NALD to assess historic patterns of agricultural demand, including the spatial distribution of patterns in licensed abstraction, derivation of a profile for the monthly timing of demand, and estimation of the relative split between surface and groundwater for irrigation abstraction in Anglian region;

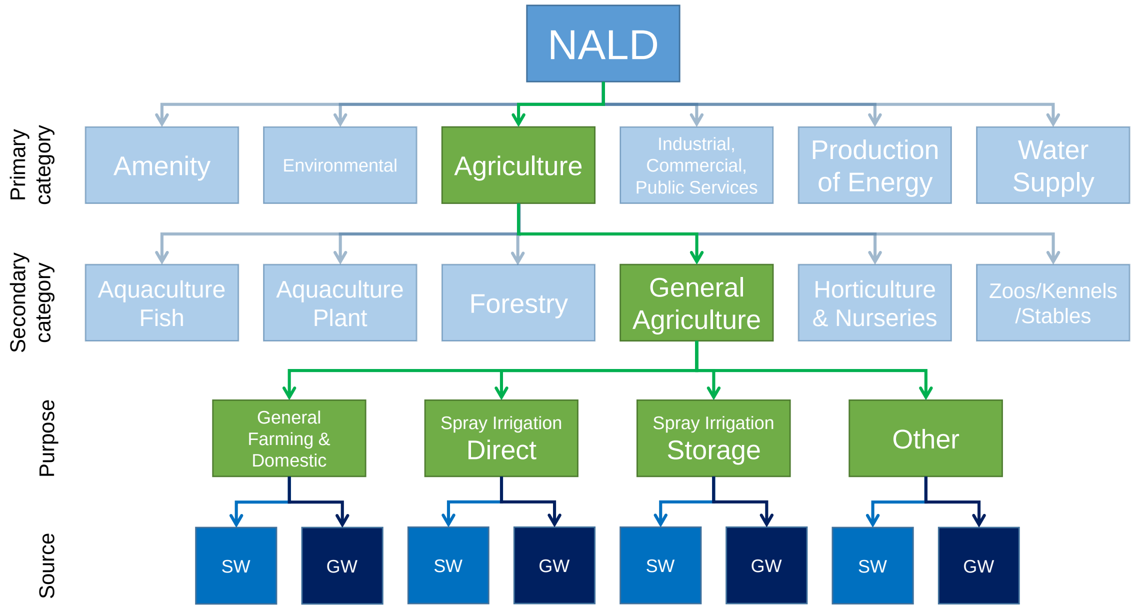
(ii) Estimation of irrigation water requirements (depths applied) for the main crop categories irrigated in the WRE region and their correlation with agroclimate variability. This was followed by modelling unconstrained irrigation demand using long-term historic climatology for each catchment, to derive annual water demand-agroclimate functions for the WRE simulator, and;

(iii) Development of a procedure (toolkit) and database to embed into the WRE simulator to spatially estimate unconstrained agricultural water demand for any defined agroclimate year (excluding effects of climate change). The procedure enables the monthly distribution of demand within each EA CAMS catchment to be estimated, as well as being able to set a ceiling above which demand is considered unrealistic. This procedure provides a useful starting point from which to assess baseline and short-term analyses of water supply/demand within the WRE region incorporating agricultural water demand.

4.1 Licensed agricultural abstraction in the WRE region

Numerous studies conducted for the EA (Weatherhead et al., 2010) and Defra (e.g. Knox et al., 2013) have involved detailed assessments of the spatial and temporal composition of licensed and abstracted volumes for agricultural spray irrigation in England and Wales. These analyses were derived from data in the EA National Abstraction Licensing Database (NALD), which are available for research purposes. The NALD database contains a historic record of abstraction licenses and volumes abstracted by source (groundwater, surface water and tidal water), with data divided into three levels, (i) primary, (ii) secondary, and (iii) purpose. In addition, water source can be considered a fourth level (Figure 2).

Figure 2 Primary and secondary NALD categories, including purpose and source.



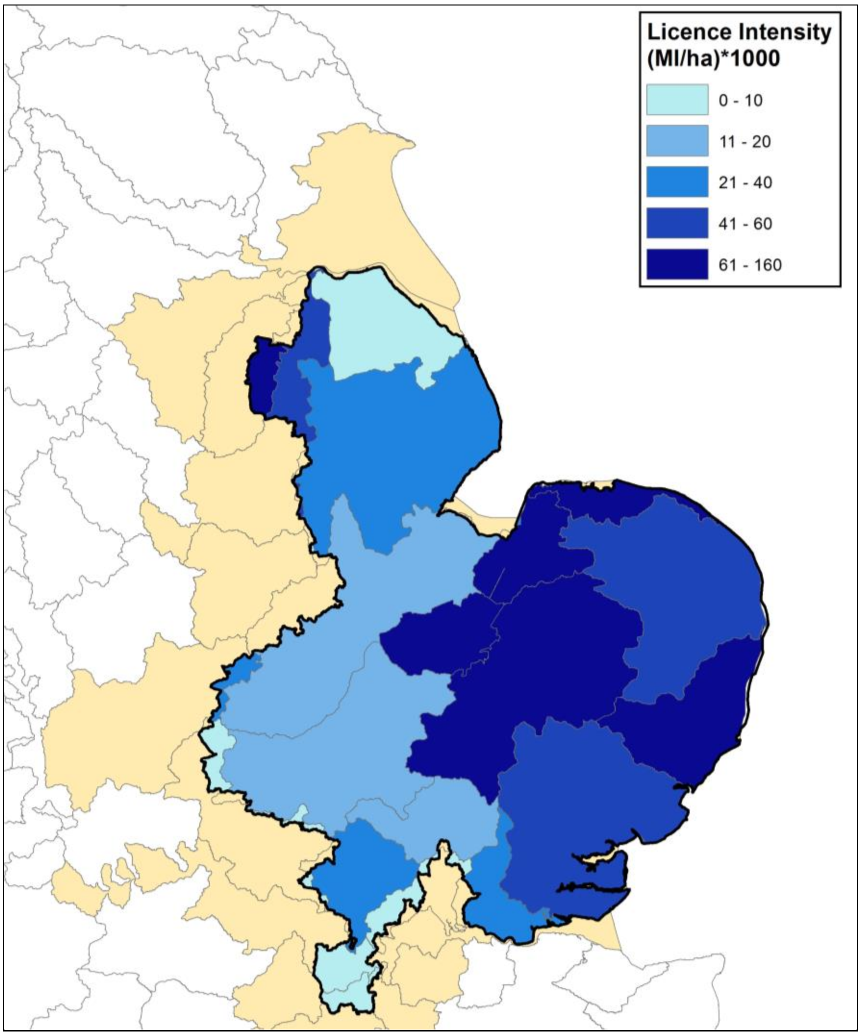
There are seven 'secondary categories' related to agriculture, namely: aquaculture fish; aquaculture plants; forestry; general agriculture; horticulture and nurseries; orchards; and zoos/kennels/stables. Due to confidentiality constraints, in this study, only existing published data relating to the 'Agriculture' category has been considered. A summary of the average licensed volume (Ml) for general agriculture by catchment is shown in Table 2. Most of the licensed volume is for direct spray irrigation (71%), followed by storage (28%) and other uses such as anti-frost irrigation (1%).

Table 2 Average licensed volume (Ml) for general agriculture, by catchment in the WRE region.

EA CAMS catchment	Licensed volume (Ml)	Propn total (%)	Licence intensity (Ml/ha)	Source	
				SW (%)	GW (%)
Cam and Ely Ouse (incl South Level)	53,625	28.8	0.146	62.9	37.1
Broadland Rivers	22,234	11.9	0.070	32.4	67.6
Combined Essex	19,158	10.3	0.055	80.8	19.2
Witham, Steeping, Great Eau, Long Eau	16,810	9.0	0.045	84.4	15.6
East Suffolk	15,964	8.6	0.098	48.6	51.4
Old Bedford (incl Middle Level)	11,857	6.4	0.129	97.9	2.1
North West Norfolk	10,372	5.6	0.109	49.4	50.6
Louth, Grimsby and Ancholme	6,078	3.3	0.042	59.2	40.8
North Norfolk	5,773	3.1	0.114	26.3	73.7
Upper and Bedford Ouse	5,349	2.9	0.018	74.5	25.5
Welland and Nene	4,988	2.7	0.015	83.9	16.1
Idle and Torne	4,346	2.3	0.168	65.7	34.3
Lower Trent and Erewash	3,546	1.9	0.055	53.7	46.3
Colne	3,363	1.7	0.034	72.6	27.4
Roding, Beam and Ingrebourne	3,197	1.7	0.047	93.0	7.0
Upper Lee	2,008	1.1	0.019	52.9	47.1
Warwickshire Avon	499	0.3	0.034	89.5	10.5
Thames Corridor	295	0.2	0.010	26.4	73.6
Wey	256	0.1	0.016	34.0	66.0
Cherwell, Thame and Wye	105	0.1	0.004	82.8	17.2
Mole	8	0.0	0.005	81.3	18.7
Total	**189,687**	**100**	**0.06**	**63.2**	**36.8**

Irrigated agriculture represents a small proportion of agricultural land use in the WRE region. However, it is an essential component of production for some crop types including potatoes, field vegetables and soft fruit (Knox et al., 2010). Abstractions tend to be concentrated in areas with low summer rainfall on low moisture retentive soils and on certain crops where irrigation serves to assure high quality and yield. Annual levels of abstraction are highly dependent on patterns of summer rainfall. The Defra 2010 Irrigation Survey showed that potatoes and vegetables accounted for 80% of the total volume of water used to irrigate crops in England with the majority (75%) concentrated in the Midlands and Anglian regions (EA, 2015). The theoretical irrigation water demands in a 'design' dry year, for a range of crop types were previously calculated for England and Wales by Knox et al. (2013). Drawing on this data, the total volumetric demand for irrigated crops in the WRE was estimated by Knox et al (2016) to be 58 Mm^3/year based on 2010 cropping. On average, licenses for spray irrigation in the WRE equate to 166,000 Ml/year, of which approximately 69% corresponds to surface and 31% to groundwater. Three large catchments (Broadland Rivers, Cam and Ely Ouse and Combined Essex) contain nearly half the total licensed volume for spray irrigation in the WRE (49.4%) Conversely, there are a number of catchments that, despite having a large proportion within the WRE region constitute <1% of total volume licensed for spray irrigation, namely the Cherwell, Thame and Wye, Mole, Thames Corridor, Warwickshire Avon, and Wey.

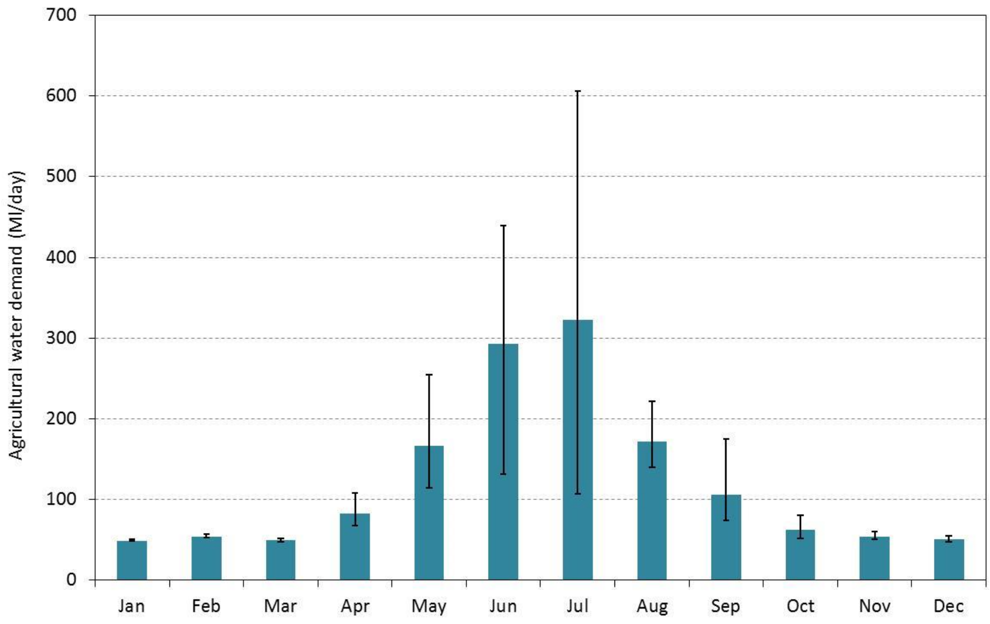
Figure 3 Spatial distribution of licensed intensity (Ml/ha) for agriculture in the WRE region.



The monthly timing of abstraction for irrigated agriculture is as important as the total volume abstracted over a cropping season. Unlike PWS abstractions, agricultural demand varies markedly through the year depending on the crop mix, agronomic demand for water to meet crop transpiration, soil conditions and ambient weather conditions (balance between rainfall and evapotranspiration). Short season high-value crops have quite different water demand profiles to longer season, deeper rooting crops. Similarly, the target markets destined for irrigated produce also affect water demand, depending on yield and quality assurance criteria (whether crops are for fresh or processed markets).

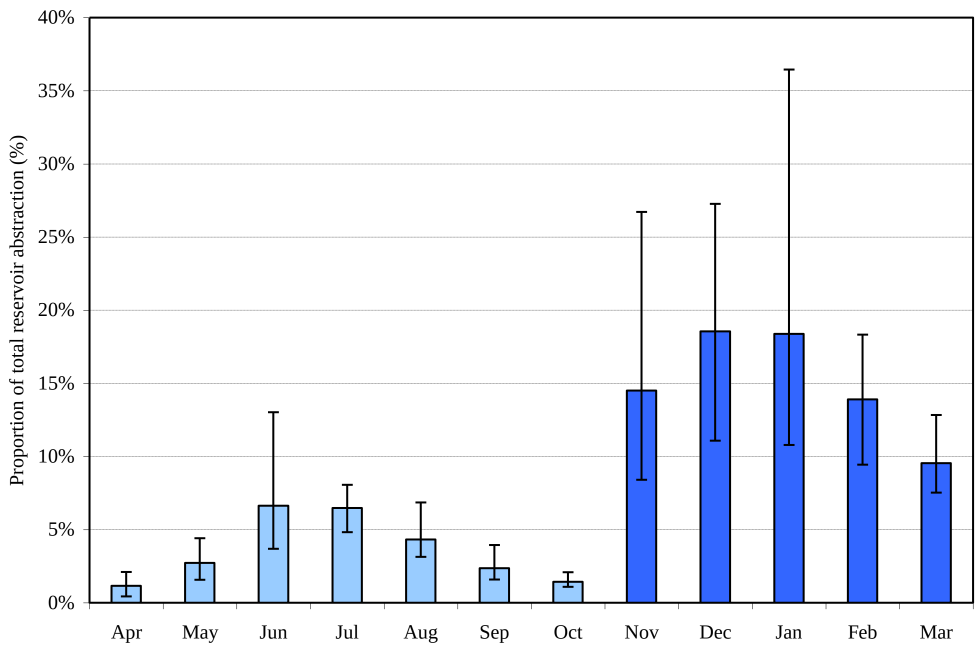
Abstraction for spray irrigation rises in the spring (April-May), peaks in summer (July-August) and then declines through late summer/autumn. The timing and proportion abstracted each month also varies from year to year (Figure 4). More than two thirds of abstraction (68%) typically occurs between June and August, with the peak month (July) accounting for more than a quarter (27%) of abstraction. The error bars highlight the significant inter-annual variation in abstraction. On average, the peak summer abstraction is around 350 Ml/day (equivalent to 10.8 Mm^3/month) but this can almost double in a dry year to around 600 Ml/day (equivalent to 18.8 Mm^3/month). This is equivalent to just over half the volume that Anglian Water put into public water supply on an average day. The highest abstraction in 2010 with a peak abstraction in July was equivalent to almost twice that recorded in 2005 (roughly equivalent to an ‘average’ year). Conversely, wetter years such as 2007 show a much lower volume and less peaked pattern of demand.

Figure 4 Monthly timing of spray irrigation demand (Ml/day) in the WRE region based on 2010. Error bars show the reported inter-annual variation between 2005 and 2010 (Source: Knox et al., 2015).



An increasing proportion of water being used for irrigated agriculture is abstracted from storage reservoirs, filled during the winter months (high flows). After initial filling, the volumes abstracted are to replace the losses and water used during the preceding irrigation season. The typical timing of water abstraction for reservoir storage is shown in Figure 5.

Figure 5 Timing of water abstraction for storage, expressed a proportion of total abstraction for storage, based on EA NALD data for 2000 to 2006. Error bars show the maximum variation over the period (Source: Weatherhead et al., 2008).



4.2 Modelling baseline (unconstrained) agricultural irrigation demand

This section describes the procedure developed to spatially estimate agricultural irrigation demand for integration into the WRE simulator. The methodology combines water balance modelling using WaSim (Hess and Council, 2009) to derive theoretical irrigation needs (depths applied, mm) with volumetric data on historical patterns of abstraction. In contrast to arid and semi-arid environments where irrigation demand can fluctuate only marginally from year to year (assuming cropping patterns remain constant), irrigation in a temperate or humid climate such as Eastern England is supplemental to rainfall. Unconstrained irrigation demand therefore varies from year to year depending on the balance between evapotranspiration (ET) and summer rainfall, which influences the proportion irrigated (%) and hence irrigated area (ha). Depths of water applied vary depending on crop type, soil water holding characteristics, irrigation management practices (scheduling), equipment availability, and the time of year.

While the variability in irrigated area can be attributed to many external reasons including agro-economic factors, the market and customer preferences, irrigation water requirements (depths applied) are almost entirely dependent on agro-climatic factors. Therefore, the approach adopted here was to estimate agricultural demand using 'theoretical' irrigation water requirements for a set of representative crop types assuming a constant irrigated area reflecting current (baseline) socio-economic conditions. This enables a linear correlation between irrigation need and agroclimate to be established. Recent abstraction data were then used to determine the monthly timing (split) in demand and the relative proportions abstracted from surface and groundwater.

Estimating theoretical irrigation demands assumed 63 permutations per CAMS catchment (including 7 main crop categories × 3 soil types reflecting contrasting available water capacities × 3 irrigation plans per crop type × agroclimate based on 116 years daily data). Irrigation water requirements (mm) were transformed into demand (Ml) based on the area irrigated of each crop type (ha) in each CAMS catchment (assuming 2010 land use). These data were then aggregated into a single time series of irrigation demand for 116 years. These were then correlated against a separate agroclimate dataset using maximum potential soil moisture deficit ($PSMD_{max}$) as an aridity indicator, for each CAMS catchment.

Knox et al. (1997) and later Weatherhead et al. (2002) studied the relationships between agro-climate and theoretical irrigation water requirements (IWR, mm/year) for a number of crops representative of UK irrigated agriculture. These studies derived linear regression equations (with the format shown in Equation 1) for eight crop categories. These included early potatoes, maincrop potatoes, sugar beet, cereals, grass, vegetables, small fruit and orchard fruit. Modelling was based on three soil types depending on their available water capacity (AWC) – low, medium or high – and against annual maximum potential soil moisture deficit ($PSMD_{max}$).

$$IWR = a.PSMD_{max} + b \qquad \text{Eq. 1}$$

$PSMD_{max}$ (mm) is an agroclimatic index that combines precipitation (P) and reference evapotranspiration (ET_o) to determine the potential soil moisture deficit at each time step of the calculation (Equation 2), with *a* ($year^{-1}$) and *b* (mm/year) being constants for each crop type and soil AWC type.

$$PSMD_t = PSMD_{t-1} + ET_{o_t} - P_t \qquad \text{Eq. 2}$$

The daily time step climate data time series is initialised to zero on the first day of every year, so a $PSMD_{max}$ value is calculated for each year as the maximum value in that year.

This study adopted a similar approach to that used previously by Knox et al 92013) although higher temporal and spatial resolution data for the WRE region were used. Irrigation water requirements (mm) were calculated for the same crop categories at CAMS catchment level using the WaSim soil water balance program (Hess 1996) with daily time step climate data for the period 1900 to 2014. The climatology dataset for the WRE region was derived from a combination of climate products including CEH-GEAR (Keller et al., 2015) and the 20th Century Reanalysis dataset (20CR) (Compo et al. 2011).

WaSim is a soil water balance program developed at Cranfield University that has been widely used internationally to estimate irrigation needs. It has been applied to assess water needs for agriculture in Scotland (Knox et al., 2007) and to estimate the effects of changes in rural land management on catchment runoff (Hess et al., 2010; Holman et al., 2011). The WaSim model requires data input relating to (rainfall and ETo), crops, soils and irrigation scheduling. The same eight crop types as used by Knox et al. (1997) were defined but updated using more recent cropping calendar and irrigation scheduling data derived from EA (2000) and Knox et al (2013). The annual theoretical volumetric irrigation demand for crop *i* (ID_i, Ml/year) was estimated (Equation 3):

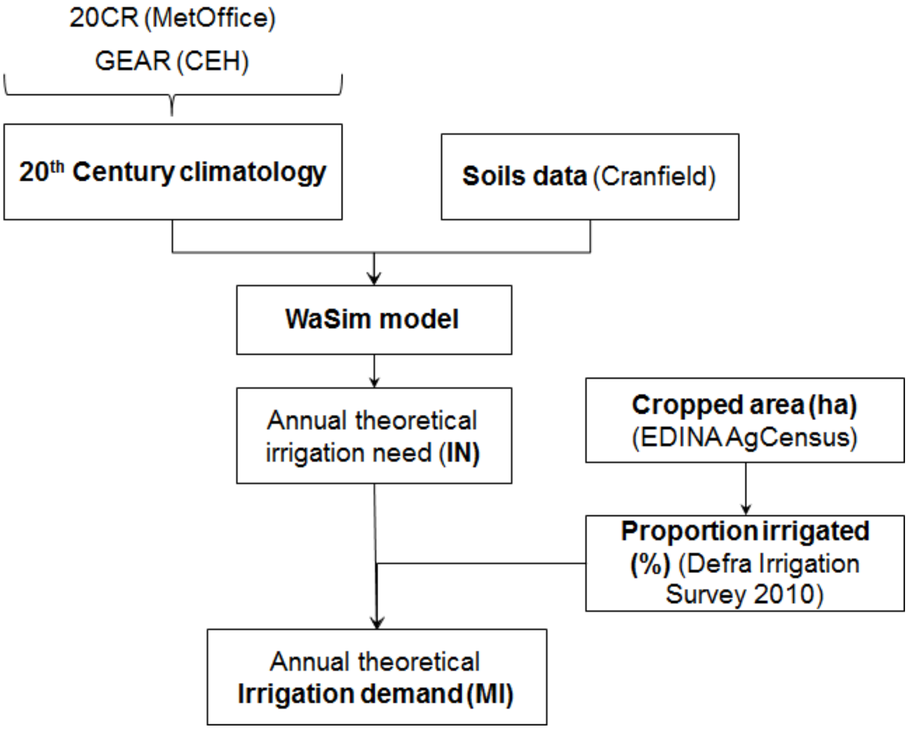
$$ID_i = \frac{IWR_i \cdot AREA_i}{100} \quad \text{Eq. 3}$$

Where $AREA_i$ is the irrigated area (ha) of crop *i* estimated from the latest Defra Irrigation Survey (2010) and the EDINA Agricultural and Horticultural Cropping Census data (AgCensus). For each CAMS catchment, the volumetric irrigation demand for each crop type was estimated, and then aggregated to a single CAMS catchment demand (Equation 5).

$$ID_{CAMS} = \sum_{i=1}^{ncrops} ID_i \quad \text{Eq. 5}$$

This 116 year irrigation demand time series was then correlated against the agroclimate variable ($PSMD_{max}$) using linear regression to estimate the total annual irrigation demand within each CAMS catchment (Figure 5).

Figure 6 Schematic flowchart to estimate theoretical annual theoretical irrigation demand (unconstrained), by CAMS catchment.



Climate data

For modelling irrigation demand, long-term daily time-step weather data from the 20th Century were used. Rainfall was extracted from the CEH-GEAR climatology (Keller et al., 2015). This dataset contains 1 km^2 grid resolution daily and monthly areal rainfall estimates for the UK. Reference evapotranspiration (ETo) was calculated using the Penman-Monteith formula and climatic data from the latest UK Met Office simulations of regional climate from the HadRM3P model, within the boundary conditions of the 20th century reanalysis (20CR) dataset (Compo et al. 2011). This dataset provides daily time-step data from 1850 to 2014 at a 25 km grid resolution. Given the different resolutions of both datasets, they were aggregated at the CAMS catchment level using a GIS.

Cropped and irrigated areas

Cropped area data were obtained from the EDINA's AgCensus data for 2010 for England which provide a spatial aggregation of the results from the Defra Agricultural Cropping Census (Defra, 2011). Irrigated areas were estimated as a proportion of the cropped area using data from the 2010 Defra Irrigation Survey (Defra, 2011). The year 2010 was selected due to accessibility of the data required as well as it closely representing a 'design' dry year in climatological terms (Knox et al., 2013). Previous research has shown that irrigated agriculture represents a small proportion of agricultural land use in the WRE region (Knox et al. 2016). Despite only 3.2% of the cropped area being irrigated, the percentage varies significantly between individual crop types and between CAMS catchments Table 3.

Table 3 Cropped areas (ha) and percentage irrigated in WRE region.

Crop type	Cropped area (ha)	Proportion irrigated (%)
Earlies potatoes	8,991	35
Maincrop potatoes	31,878	59
Sugar beet	93,735	6
Orchards	1,860	0
Soft fruit	1,274	10
Vegetables	53,087	24
Cereals	904,041	1
Other	365,050	0.5
Total	**1,459,917**	**3.5**

Note: Defra Agricultural Cropping Census and Irrigation Survey (2010).

Potatoes constitute the most irrigated crop with more than 50% of the cropped area, followed by field vegetables. Seven of the 20 CAMS within the WRE region contain nearly 85% of the total irrigated area (including Broadland Rivers, the Cam and Ely Ouse, Combined Essex, East Suffolk, Old Bedford, Welland and Nene, and Witham Steeping, Great Eau and Long Eau). The Cam and Ely Ouse catchment has the largest irrigated area. Further information on the composition on agricultural land use in the WRE region is given in the WRE scoping report (Knox et al. (2016). A summary of the estimated cropped and irrigated areas, by CAMS catchment in the WRE region is given in Table 4.

Table 4 Cropped and irrigated areas per CAMS within WRE region. The areas have been weighted according to the percentage of surface within WRE considering an even distribution.

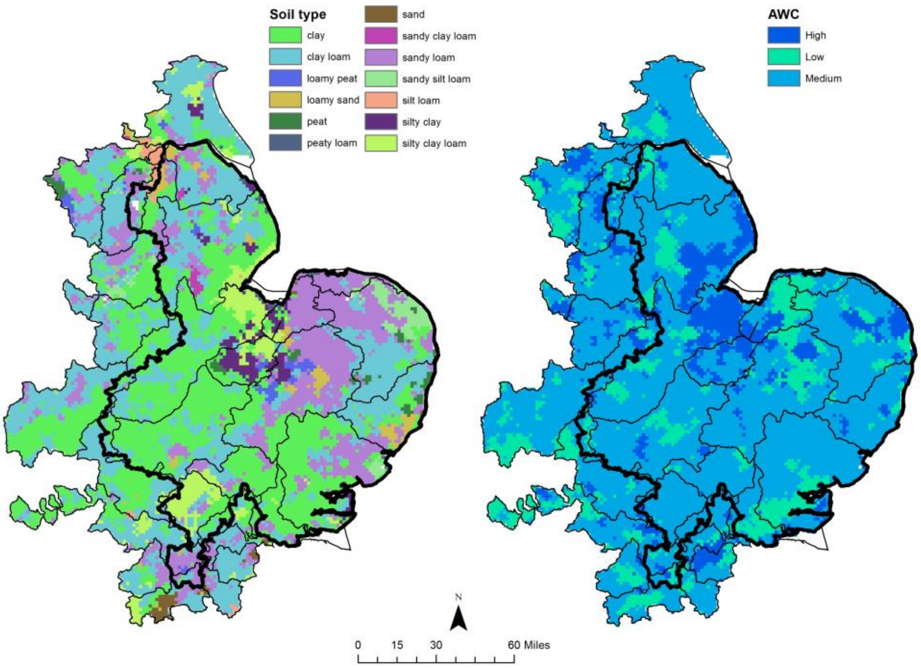
CAMS catchment	Cropped area (ha)	Irrigated area (ha)	Prop irrigated (%)	Propn WRE irrigated (%)
Cam and Ely Ouse (incl South Level)	184,725	11,632	6.3	23.2
Broadland Rivers	156,410	7,267	4.6	14.5
Old Bedford (incl Middle Level)	59,360	5,288	8.9	10.6

CAMS catchment	Cropped area (ha)	Irrigated area (ha)	Prop irrigated (%)	Propn WRE irrigated (%)
Witham, Steeping, Great Eau, Long Eau	225,286	5,212	2.3	10.4
Welland and Nene	175,448	4,848	2.8	9.7
Combined Essex	169,642	4,184	2.5	8.4
East Suffolk	78,153	3,444	4.4	6.9
North West Norfolk	49,869	2,610	5.2	5.2
Upper and Bedford Ouse	131,698	1,536	1.2	3.1
North Norfolk	18,956	1,146	6.0	2.3
Louth, Grimsby and Ancholme	73,171	990	1.4	2.0
Roding, Beam and Ingrebourne	18,783	534	2.8	1.1
Upper Lee	46,388	526	1.1	1.1
Lower Trent and Erewash	26,643	361	1.4	0.7
Idle and Torne	9,532	210	2.2	0.4
Colne	14,151	110	0.8	0.2
Warwickshire Avon	5,079	65	1.3	0.1
Cherwell, Thame and Wye	9,627	45	0.5	0.1
Thames Corridor	5,262	20	0.4	0.0
Wey	1,631	17	1.0	0.0
Mole	104	0	0.5	0.0
Total	**1,459,917**	**50,046**	**3.5**	

Soils data

The spatial distribution of soil types across the WRE region were derived from existing databases held by Cranfield University. Thirteen typologies were identified of which clay was the most representative, followed by sand (Figure 7, left panel). In terms of available water capacity, soils around The Wash had the highest content, whilst most of the remaining WRE region was dominated by medium available water content soils (Figure 7, right panel).

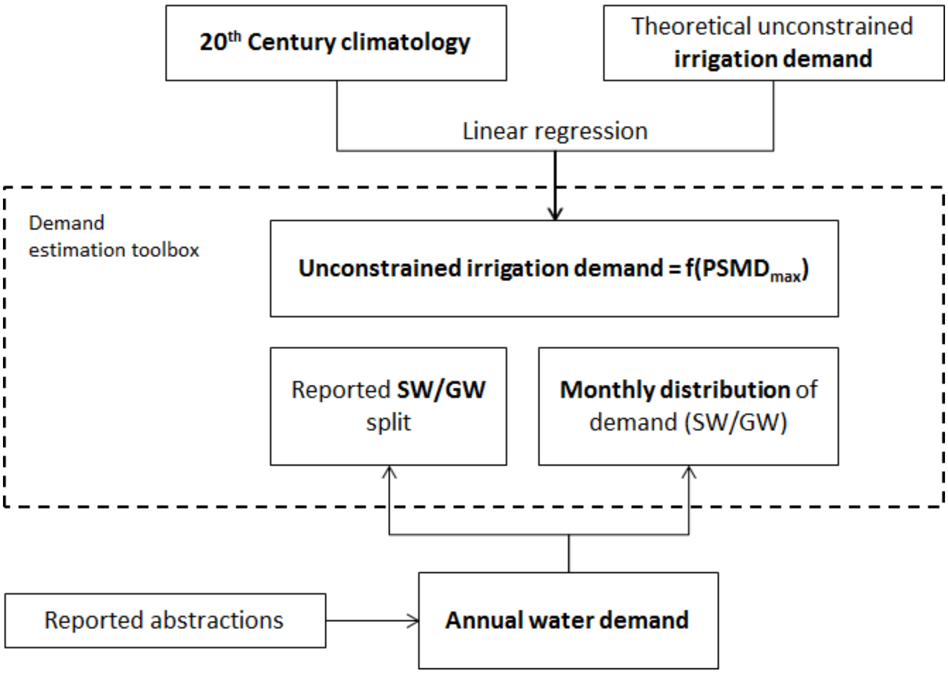
Figure 7 Soil type (left panel) and available water content (right panel) in the WRE region.



4.3 Irrigation demand estimation toolbox for WRE simulator

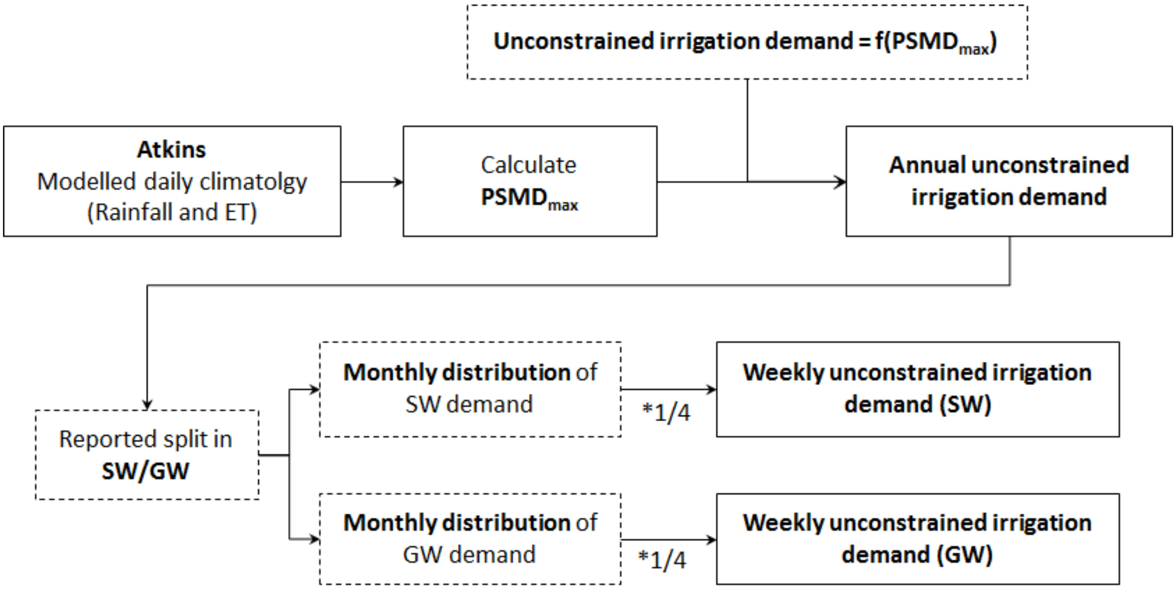
The WRE simulator will run on a weekly time-step and needs to consider abstractions from both surface and groundwater. Thus, the irrigation demands presented in Section 4.2 need to be disaggregated by water source. By combining data on sources and timing of abstraction (Section 4.1) with estimates of volumetric demand (Section 4.2) a demand estimation toolbox has been created for the WRE simulator. The toolkit adopts a cascade approach (Figure 8)

Figure 8 Components of the irrigation demand estimation toolbox for the WRE simulator.



The $PSMD_{max}$ for a given year and CAMS catchment is first calculated using climate data (P and ETo) within the Atkins simulator; the $PSMD_{max}$ value is then used in the appropriate linear regression formula (Table 6) for each CAMS catchment; the proportional split in demand between surface and groundwater is then derived; the annual demand for each water source is disaggregated according to the monthly distribution (Table 7 and Table 8); finally, the monthly values can be further split into weekly based estimates (Figure 9).

Figure 9 Schematic showing the agricultural irrigation demand estimation toolbox.



5. Modelling outputs

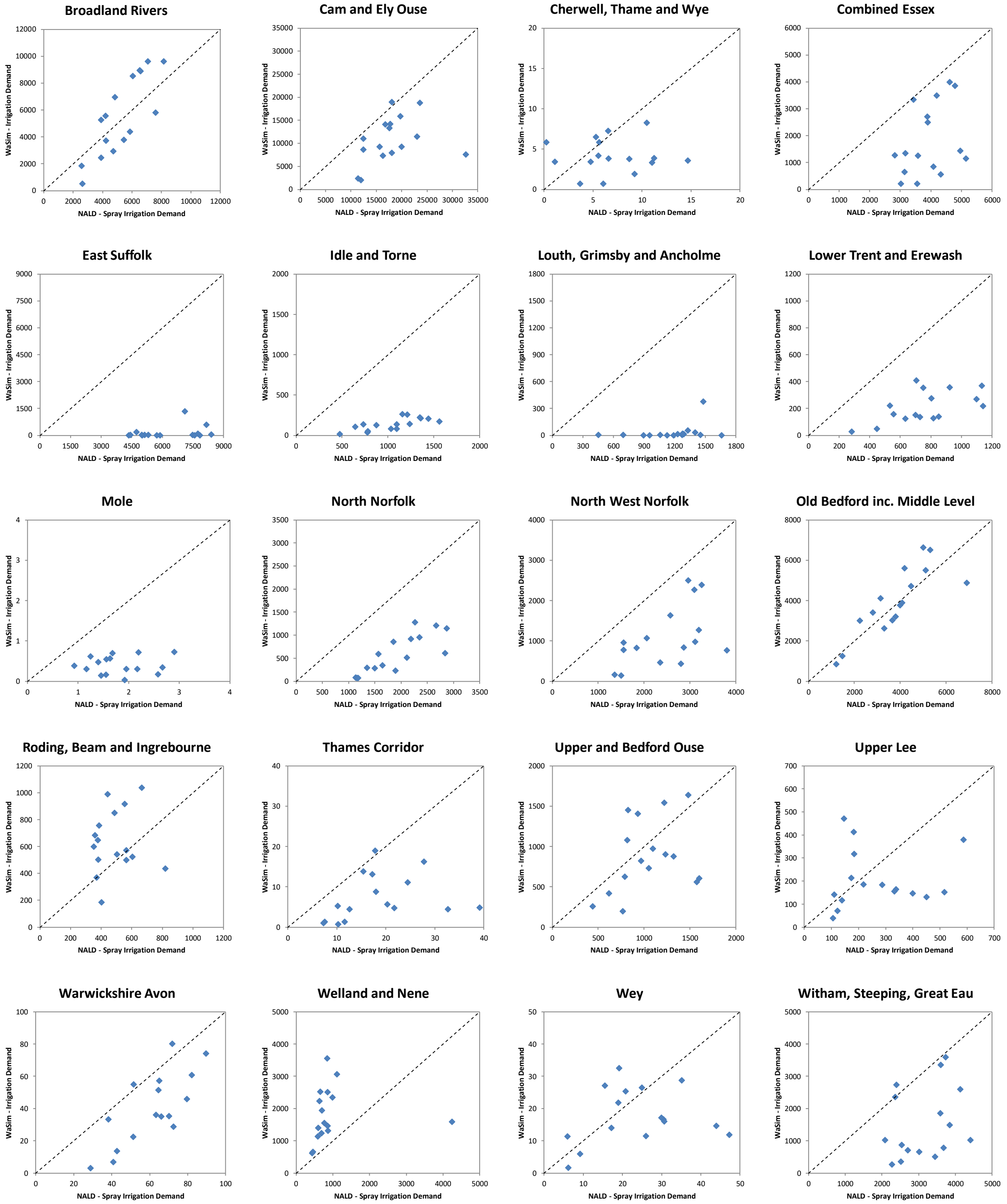
5.1 Correlating irrigation demand, agroclimate and abstraction

Overall, the derived correlations between theoretical irrigation demand and agroclimate are good (Table 5), although the statistical significance is slightly lower for some CAMS than others (those with small irrigated areas and/or niche crop mixes). In contrast, the performance of the model against reported abstractions tends to be poor for most CAMS, with a general tendency towards under-estimation of theoretical demand. However, this is highly variable between individual CAMS catchments. In some, such as the Broadland Rivers, Old Bedford, and Upper and Bedford Ouse, the modelling approach provides an acceptable estimation of demand, in contrast to East Suffolk, Iddle and Torne, and Louth, Grimsby and Ancholme, where the over-estimation is more evident. There are also cases such as the Roding, Beam and Ingrebourne, and the Welland and Nene CAMS catchments where the modelling approach overestimates demand.

Table 5 Squared Pearson correlation coefficient between modelled irrigation demand and agroclimate and Mean Squared Error (MSE) between modelled irrigation demand and reported abstractions, by CAMS catchment in the WRE region.

CAMS catchment	r^2 (PSMDmax vs WaSim)	MSE (WaSim vs observed)
Broadland Rivers	0.92	3326426
Cam and Ely Ouse (including South Level)	0.93	86694511
Cherwell, Thame and Wye	0.92	25
Colne	0.93	139
Combined Essex	0.93	5934257
East Suffolk	0.64	39066391
Idle and Torne	0.94	898104
Louth Grimsby and Ancholme	0.70	1380650
Lower Trent and Erewash	0.92	335962
Mole	0.84	2
North Norfolk	0.93	1868312
North West Norfolk	0.93	2477959
Old Bedford including the Middle Level	0.94	855287
Roding, Beam and Ingrebourne	0.91	80686
Thames Corridor	0.91	204
Upper and Bedford Ouse	0.92	232433
Upper Lee	0.79	37808
Warwickshire Avon	0.91	659
Welland and Nene	0.92	2038544
Wey	0.93	210
Witham, Steeping Great Eau and Long Eau	0.93	3891676

Figure 10 Linear correlations between irrigation demand (Ml/year) estimated with WaSim and reported irrigation demand for each CAMS catchment in the WRE region.

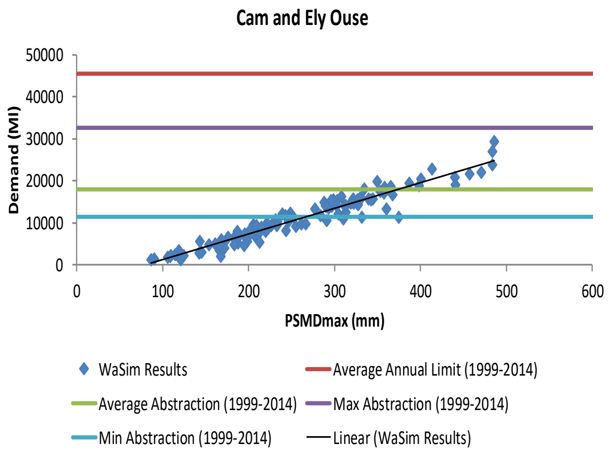


5.2 Agricultural demand estimation: example application

The demand estimation toolbox is composed of three datasets (Tables 6 to 8). Table 6 provides the relevant regression and water source data needed to estimate theoretical annual irrigation demand, by CAMS catchment. Table 7 and Table 8 provide the proportional split in volumetric demand, by month, by CAMS catchment, for surface and ground water, respectively. This section provides an example application of these datasets to derive agricultural water demand for a single CAMS catchment, the Cam and Ely Ouse.

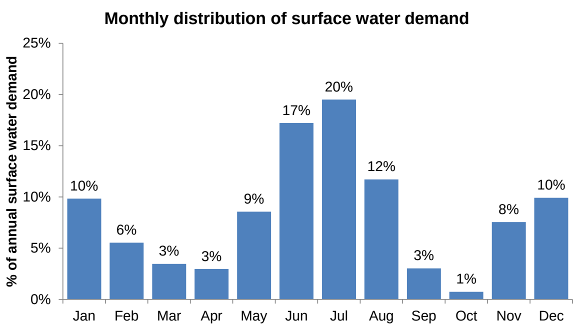
The data in Table 6 enables the volumetric irrigation demand to be estimated for a given CAMS catchment, as a function of agroclimate. In addition, Table 6 allows the derived theoretical demand to be set in context with observed/reported data. For example, in the Cam and Ely Ouse catchment the WaSim modelled outputs are used to calculate the slope and intercept values for the linear regression with agroclimate ($PSMD_{max}$) (Figure 10). The average licensed volume, maximum annual abstraction, average annual abstraction and minimum annual abstraction are highlighted. In this way, it is possible to understand the theoretical demand relative to historical use and licensed allocation. These relationships will form the basis for deriving suitable performance metrics for agriculture in the WRE simulator.

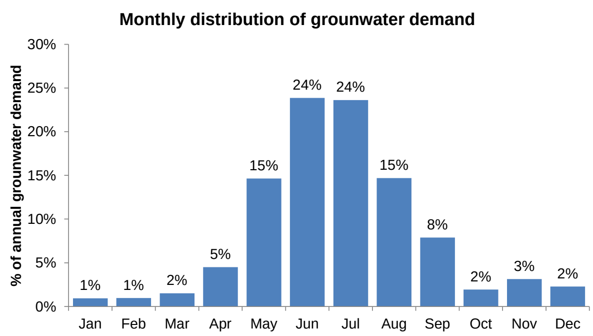
Figure 11 Graphical representation of data included in the irrigation demand estimation toolbox, for the Cam and Ely Ouse catchment.



$$\mathbf{Demand(Ml)} = \mathbf{63.5} \cdot \boldsymbol{PSMD_{max}} + \mathbf{4626}$$

Surface water use = **69%**
Groundwater use = **31%**





Irrigation demand	**Volume (Ml)**
Licensed limit	45420
Average abstraction	17975
Maximum abstraction	32680
Minimum abstraction	11388

The $PSMD_{max}$ values are first calculated from the Atkins climate data to estimate annual agricultural demand (Figure 12). The proportion of demand attributed to each source (surface and groundwater) from Table 9 can then be determined. The total demand from each source is then calculated (Figure 13). Finally, using the monthly distributions (Table 7 and Table 8), the monthly timing of demand is derived (Figure 14).

Figure 12 Estimating theoretical volumetric annual agricultural demand based on agroclimate.

$$\mathbf{Demand(Ml)} = \mathbf{63.5} \cdot \boldsymbol{PSMD_{max}} + \mathbf{4626}$$

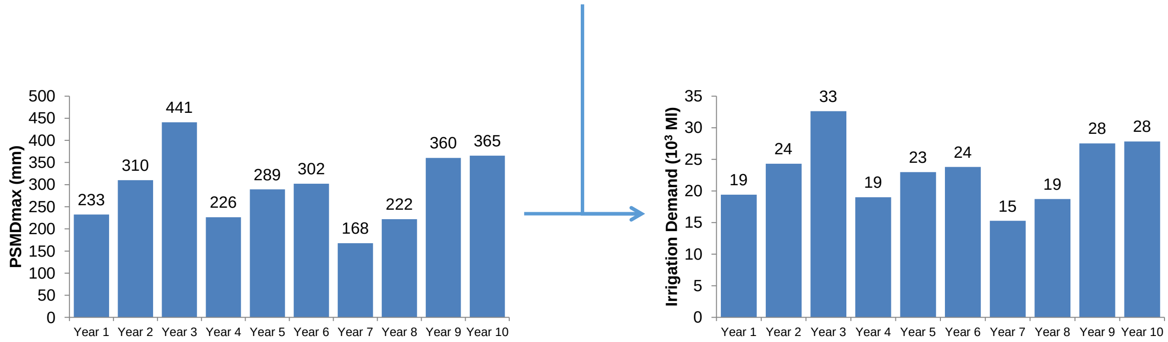


Figure 13 Estimated split in demand from surface and groundwater.

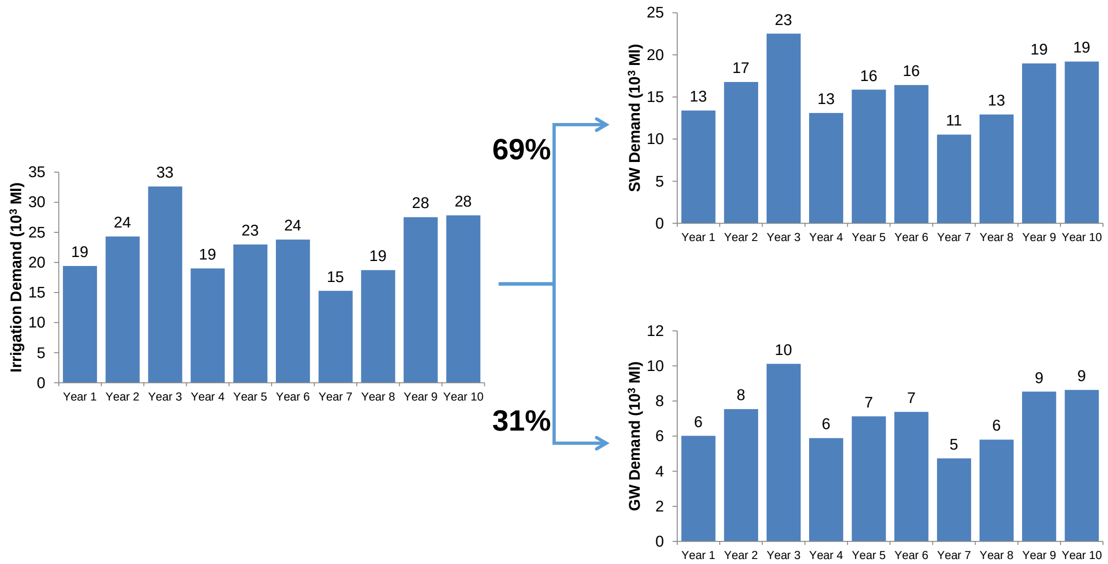


Figure 14 Monthly distribution of surface and groundwater irrigation demand.

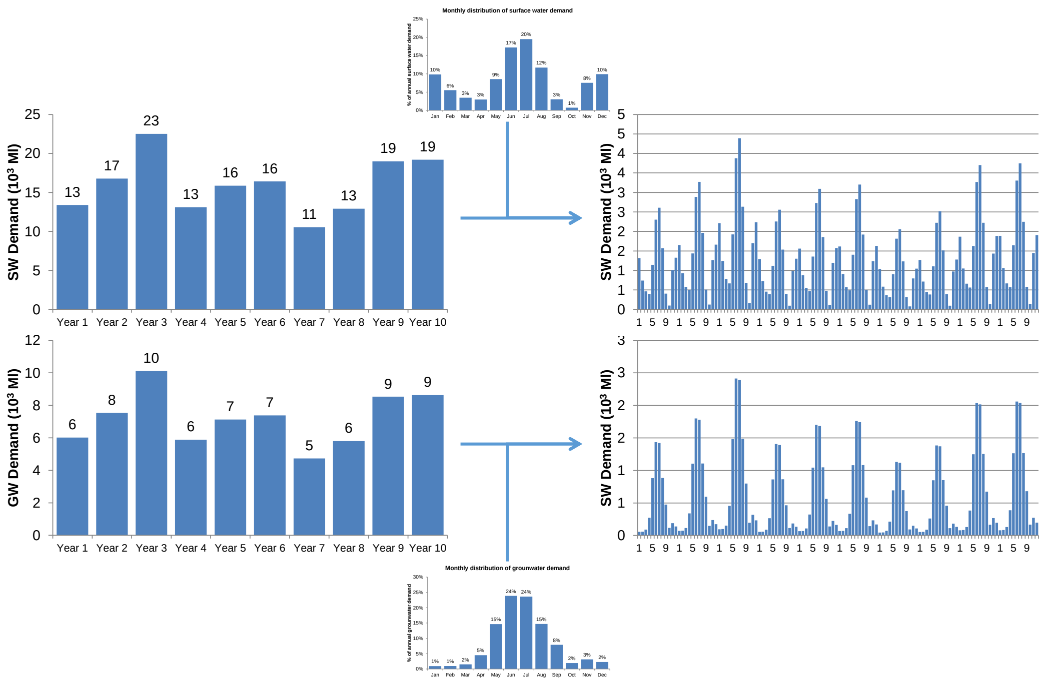


Table 6 Linear regression components for irrigation demand estimation.

CAMS catchment	Slope (Ml/mm)	Intercept (Ml)	Total licenced volume (Ml)	Max. abstraction (Ml)	Average abstraction (Ml)	Minimum abstraction (Ml)	SW use (%)	GW use (%)
Broadland Rivers	34.83	-2848	18566	8168	5269	2582	29%	71%
Cam and Ely Ouse (incl South Level)	61.49	-4985	45420	32680	17975	11388	69%	31%
Cherwell, Thame and Wye	0.02	-2	73	15	7	0	98%	2%
Colne			2325	27	9	1		
Combined Essex	18.40	-1423	17884	5141	3913	2816	83%	17%
East Suffolk	10.20	-527	14766	8389	6241	4361	55%	45%
Idle and Torne	1.05	-76	3988	1561	1052	475	63%	37%
Louth, Grimsby and Ancholme	3.57	-188	5138	1661	1172	452	57%	43%
Lower Trent and Erewash	1.71	-128	3365	1142	757	282	33%	66%
Mole	0.00	0	6	3	2	1	99%	1%
North Norfolk	6.70	-392	5628	2867	1911	1135	20%	80%
North West Norfolk	11.00	-660	9710	3802	2490	1357	42%	58%
Old Bedford including the Middle Level	20.82	-1732	11758	6895	3793	1216	97%	3%
Roding, Beam and Ingrebourne	2.54	-193	3022	818	490	352	97%	3%
Thames Corridor	0.06	-5	140	39	18	7	29%	71%
Upper and Bedford Ouse	4.92	-464	4761	1601	1045	442	83%	17%
Upper Lee	1.20	-133	1872	586	268	106	36%	64%
Warwickshire Avon	0.28	-22	427	90	61	29	88%	12%
Welland and Nene	11.02	-618	4746	4239	957	432	88%	11%
Wey	0.09	-6	153	47	24	6	46%	54%
Witham, Steeping, Great Eau, Long Eau	19.10	-1255	14233	4411	3145	2086	80%	20%

Table 7 Monthly surface water demand distribution, by CAMS catchment.

CAMS catchment	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Broadland Rivers	6%	4%	3%	3%	10%	21%	22%	13%	5%	0%	4%	8%
Cam and Ely Ouse (incl South Level)	10%	6%	3%	3%	9%	17%	20%	12%	3%	1%	8%	10%
Cherwell, Thame and Wye	15%	14%	14%	0%	1%	3%	5%	5%	3%	1%	18%	19%
Colne	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Combined Essex	13%	11%	8%	2%	6%	10%	13%	9%	3%	1%	11%	14%
East Suffolk	6%	5%	4%	3%	13%	19%	17%	12%	7%	1%	5%	6%
Idle and Torne	4%	2%	2%	2%	6%	20%	28%	18%	8%	2%	4%	4%
Louth, Grimsby and Ancholme	19%	16%	10%	2%	5%	11%	13%	7%	3%	0%	1%	12%
Lower Trent and Erewash	3%	3%	3%	2%	7%	25%	30%	15%	6%	1%	2%	2%
Mole	0%	0%	3%	8%	14%	18%	19%	15%	16%	5%	1%	0%
North Norfolk	7%	4%	3%	1%	6%	15%	22%	13%	5%	1%	9%	12%
North West Norfolk	10%	9%	5%	2%	7%	13%	16%	9%	4%	1%	8%	15%
Old Bedford (incl Middle Level)	7%	9%	1%	1%	6%	20%	26%	11%	3%	1%	7%	7%
Roding, Beam and Ingrebourne	19%	15%	11%	1%	3%	5%	6%	4%	2%	1%	15%	19%
Thames Corridor	0%	0%	1%	5%	11%	24%	27%	18%	12%	1%	0%	0%
Upper and Bedford Ouse	9%	8%	6%	3%	6%	15%	22%	12%	5%	2%	5%	7%
Upper Lee	19%	14%	8%	0%	1%	6%	11%	8%	2%	0%	18%	13%
Warwickshire Avon	2%	1%	8%	6%	10%	19%	20%	14%	10%	4%	3%	4%
Welland and Nene	6%	5%	6%	2%	5%	20%	32%	14%	7%	1%	1%	2%
Wey	4%	2%	6%	3%	8%	17%	22%	17%	11%	1%	6%	4%
Witham, Steeping, Great Eau, Long Eau	15%	14%	12%	1%	5%	14%	18%	9%	4%	1%	1%	6%

Table 8 Monthly groundwater demand distribution, by CAMS catchment.

CAMS catchment	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Broadland Rivers	0%	0%	1%	3%	12%	26%	31%	18%	7%	1%	0%	0%
Cam and Ely Ouse (incl South Level)	1%	1%	2%	5%	15%	24%	24%	15%	8%	2%	3%	2%
Cherwell, Thame and Wye	0%	0%	0%	5%	10%	28%	32%	19%	4%	1%	0%	0%
Colne	0%	0%	1%	7%	12%	26%	23%	16%	7%	7%	1%	1%
Combined Essex	1%	1%	2%	4%	15%	23%	25%	18%	7%	2%	2%	2%
East Suffolk	0%	0%	1%	5%	16%	24%	23%	17%	10%	3%	1%	0%
Idle and Torne	1%	1%	1%	3%	8%	24%	31%	19%	9%	2%	0%	0%
Louth, Grimsby and Ancholme	4%	4%	4%	5%	11%	19%	23%	15%	8%	2%	1%	3%
Lower Trent and Erewash	0%	0%	0%	3%	7%	23%	32%	20%	11%	3%	0%	0%
Mole	0%	0%	0%	11%	19%	26%	19%	18%	7%	0%	0%	0%
North Norfolk	1%	1%	1%	2%	9%	25%	32%	21%	8%	1%	0%	0%
North West Norfolk	0%	0%	0%	4%	13%	24%	29%	19%	8%	1%	0%	0%
Old Bedford (incl Middle Level)	0%	0%	0%	3%	8%	24%	34%	19%	5%	2%	2%	2%
Roding, Beam and Ingrebourne	12%	7%	15%	0%	2%	1%	2%	27%	0%	3%	10%	20%
Thames Corridor	0%	0%	3%	5%	14%	21%	23%	17%	16%	1%	0%	0%
Upper and Bedford Ouse	1%	1%	3%	9%	12%	14%	18%	18%	12%	7%	2%	2%
Upper Lee	1%	2%	1%	4%	9%	25%	32%	15%	9%	1%	0%	1%
Warwickshire Avon	1%	1%	9%	7%	12%	19%	18%	15%	10%	6%	2%	2%
Welland and Nene	3%	2%	2%	5%	12%	27%	25%	12%	5%	1%	2%	3%
Wey	0%	3%	2%	4%	7%	22%	31%	18%	11%	1%	1%	0%
Witham, Steeping, Great Eau, Long Eau	6%	5%	2%	2%	11%	24%	25%	16%	6%	1%	0%	1%

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