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Evaluation of changing surface water abstraction reliability for supplemental irrigation under climate change

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Abstract

In many temperate parts of the world, supplemental irrigation is crucial to assure both crop yield and quality. Climate change could increase the risks of irrigation being restricted by increasing crop water requirements and/or decreasing water availability. In England, water abstraction for irrigation is limited by maximum annual volumetric limits, as specified in the abstraction licenses, and surface water abstraction restrictions imposed by the regulator during drought. This paper assesses how climate change might impact future irrigation abstraction reliability from surface water in England. Firstly, the probability of annual abstraction being close to the maximum license limit was estimated for the baseline (1961-1990) and future (2071-2098) periods in each catchment based on observed relationships between annual weather and irrigation abstraction in three licence usage groups. Secondly, the current river discharge triggers for mandatory drought restrictions were used to assess the annual probability of surface water abstraction restrictions being imposed by the regulator in each period. Results indicate significant future increases in irrigated abstraction license use due to an increase in aridity, particularly in the most productive agricultural areas located in eastern and southern England, assuming no adaptation. The annual probability of having less than 20% licence headroom in the highest usage group is projected to exceed 0.7 in 45% of the management units, mostly in the south and east. In contrast, irrigators in central and western England face an increased risk of drought restrictions due to the lower buffering capacity of groundwater on river flows, with the annual probability of mandatory drought restrictions reaching up to 0.3 in the future. Our results highlight the increasing abstraction reliability risks for irrigators due to climate change, and the need for the farming community and the regulator to adapt and collaborate to mitigate the associated impacts.

Keywords: drought; England; resilience; irrigated agriculture; risk; adaptation

1. Introduction

Irrigation is crucial for sustaining the world's population, as 40% of crop production is concentrated in the 18% of total arable land that is irrigated (Fischer et al., 2007). Climate change is projected to alter temperatures, as well as the magnitude and seasonal distribution of precipitation (Arnell, 2003; Charlton and Arnell, 2011). In humid climates, a reduction of summer precipitation and an increase in the probability of extreme events such as heatwaves and droughts (Falloon and Betts, 2010; Bindi and Olesen, 2011; Weatherhead et al., 2015) are likely to increase irrigation water demand. Consequently, whilst irrigation needs are expected to increase in the future, water availability may decline in many regions due to climate change and competing demands for water (FAO, 2002; De Silva et al., 2007; Rodriguez Diaz et al., 2007; Charlton and Arnell, 2011; Gerten et al., 2011).

This tri-lemma of reduced water resource availability, increased irrigation demand and increasing competition between water users will require regulatory bodies to actively manage abstraction to ensure water resources sustainability and environmental protection (Henriques et al., 2008; Weatherhead and Howden, 2009). In Europe, governments have their own national legislation and abstraction management rules, described by Mills and Dwyer (2009), in addition to European regulations. For example, financial charges are payable in Germany according to the volume of water abstracted; France also applies volumetric charges and water users require a permit to abstract more than $8m^3/h$; similarly, Denmark uses a time-limited permit system for ground and surface water abstraction; and Belgium, Netherlands and the United Kingdom have compulsory registration and licensing systems, in which abstraction can be restricted during severe droughts.

In England, an abstraction licence is required from the Environment Agency (EA) to abstract more than 20 m^3/day from surface or groundwater (Environment Agency, 2013). However, having an irrigation abstraction licence does not entitle the licence holder to always be able to abstract, as the EA can impose partial or total bans on irrigation abstraction from surface water sources during droughts to protect public water supplies and the aquatic environment (Environment Agency, 2015). Such restrictions on supplemental irrigation can have severe impacts on crop yield and quality leading to considerable financial losses - Rey et al. (2016) assessed the net financial benefits of supplemental agricultural irrigation at the farm level in a dry year at over £660 million in England and Wales, using current irrigated cropping and market data. Irrigation is mainly concentrated in central and eastern England, where many catchments are already assessed by the EA as “over-abstracted” or “over-licensed” (Hess et al., 2011) and therefore vulnerable to future pressures on water resources.

In this global context of climate change, increasing irrigation needs and increasing likelihood of water management constraints, this paper provides the first national scale assessment of how climate change will impact the future reliability of supplemental irrigation from surface water. Focusing on England as a case study, it assesses the changing annual risk of individual farmers being unable to meet future irrigation demand due to having an insufficient annual licensed volume and/or being subject to mandatory restrictions on surface water abstraction during droughts. The paper has broader relevance as the analysis can be replicated in other countries to understand how climate change could affect water availability for irrigators.

2. Material and methods

There are five main stages to the analysis (Figure 1). Firstly, explanatory relationships between actual annual licence usage by irrigators in the period 1999-2011 and an annual agroclimatic indicator of aridity (annual maximum Potential Soil Moisture Deficit, PSMD) are derived from observed data for each of the 85 Catchment Abstraction Management Strategy (CAMS) units in England (Step 1). Secondly, the relationships obtained in Step 1 are applied to baseline (1961-1990) and future (2071-2100) annual PSMDmax calculated from (FFC) (Step 2), assuming stationarity in crop spatial distribution and irrigation efficiency, to estimate the annual probability of irrigators in each CAMS being constrained by the volumetric abstraction license limit for each period. Thirdly, the drought management rules currently used by the Environment Agency are applied to the simulated timeseries of daily river flow and rainfall data for the baseline period (1961-90) from the Future Flows Climate (FFC) and Future Flows Hydrology (FFH) datasets, respectively, to calculate the daily river flow and rainfall triggers for mandatory restrictions on irrigation abstraction (Step 3). Fourthly, the restriction triggers in Step 3 are applied to simulated baseline and future (2071-2100) daily river flows (FFH) and rainfall (FFC) to estimate the annual probability of irrigators in each CAMS being under mandatory drought restrictions (Step 4). Finally, a combined risk metric was calculated based on the results from Steps 2 and 4, representing the annual probability for irrigators being close to their volumetric license limit and being under mandatory drought abstraction restriction (Step 5). Results from the baseline and future periods were then compared to assess the direct and indirect climate change impact on surface water reliability for irrigation in every catchment across England.

2.1. Data

2.1.1. Climate data

Two sets of climate data are used: i) a 5km x 5km UK Meteorological Office gridded dataset of observed monthly precipitation and derived reference evapotranspiration estimated using the FAO Penman-Monteith equation (Allen et al., 1998) from 1961 to 2011; ii) the Future Flows Climate (FFC) dataset (Prudhomme et al., 2012b), a national-scale set of high resolution transient climate change projections of precipitation and reference evapotranspiration for 1950 to 2098 based on 11 different variants of a regional climate model, that captures climate modelling uncertainty. This 11-member ensemble is based on HadRM3-PPE (Met Office Hadley Centre's Regional Climate Model Perturbed Physics Ensemble) under the SRES A1B emissions scenario (Special Report on Emissions Scenarios; IPCC, 2000), which was used as part of the derivation of the current (UKCP09) scenarios[1] (Murphy et al., 2009).

FFC was generated after bias-correction of HadRM3-PPE projections of precipitation and temperature. For each ensemble member and variable, monthly transfer functions were applied so that bias-corrected time series matched the distribution of corresponding gridded

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[1] AlB is broadly similar to the Representative Concentration Profile (RCP) 6.0 (Melillo et al., 2014).

observational data over the period 1962-2000 (Prudhomme et al., 2012b). Snow melt processes were accounted for using a simple elevation-dependent snow-melt model, and reference evapotranspiration projections were estimated based on the FAO Penman-Monteith equation (Allen et al., 1998). In this study, the 11 ensembles were individually investigated to include a broad description of the natural climate variability in the analysis. As they are equally probable, the results were pooled together thereafter and considered as a single population.

2.1.2. Irrigation abstraction data

The annual volumetric licence limit and actual monthly abstraction for the period 1999-2011 for 3,738 groundwater and surface water summer abstraction licences for irrigation in England were obtained from the Environment Agency (EA) for the 85 CAMS units, which are the spatial units by which the EA manages water resources (Environment Agency, 2013). For the purpose of this paper, only CAMS having at least 10 surface water irrigation licences were included in the analysis (Figure 2a). The focus is on surface water licences only, as groundwater abstraction is not affected by mandatory abstraction restrictions in drought periods. Although the split between surface water and groundwater abstraction varies considerably between catchments (Figure S1 from the Supplementary Material), abstraction from surface water for irrigation is significant (Figure 2b)- in the most recent drought year (2011), more than 50% of total abstraction for spray irrigation in England was from surface water.

The EA abstraction dataset does not provide any information on associated irrigated crop types or irrigated areas for each license. Furthermore, no datasets exist on the spatial distribution of irrigated crops in the country, so it is not possible to project licence-specific annual volumetric irrigation need (Rees et al., 2003). However, according to the latest irrigation survey (Defra, 2011), potatoes represent more than 40% of the total irrigated area in England, followed by vegetables (24%).

Given the absence of this data and the focus of the paper on understanding the reliability of surface water irrigation abstraction licences, the license dataset was standardized by using the annual abstraction data of each license to derive the proportion of the annual licensed volume that was not abstracted in a given year i.e., the annual headroom, expressed as a proportion of the licence limit. For each CAMS, non-used (so-called "sleeper") licences were removed and the remaining licences were sub-divided into 3 groups based on the relative likelihood of having insufficient headroom under current and future climates: 1) *a low headroom group*, defined as the 25% of licences with the lowest headroom, who are currently at risk of having insufficient water in dry years; 2) *a medium headroom group*, with licences between the 25th and 50th percentile of headroom, who currently have a little risk of having insufficient headroom but may have a future risk in dry years; and 3) *a high headroom group*, for the remaining 50% of licences, who are unlikely to have insufficient headroom in current or future dry years. Each group represents a different abstraction behaviour. The low headroom group is representing risk-accepting growers that are using most of their licence volume each year; the medium headroom group use a big part of the licence volume but in general they have enough spare capacity to face dry conditions and represent more risk-averse or land-constrained growers; and the high headroom group is representing irrigators who currently grow limited areas of irrigated crops

2.1.3. Hydrological data

The Future Flows Hydrology (FFH) dataset (Prudhomme et al., 2013) is an 11-member ensemble of daily river flow simulations, using FFC (described in Section 2.1.1) as climate input. For consistency in the modelling, the subset of FFH generated by the CERF

(Continuous Estimation of River Flows) regionalized rainfall-runoff model (Griffiths et al., 2006), containing 85 catchments across England and Wales, was used here. CERF was calibrated across all catchments simultaneously to obtain a best model fit across all catchments, with model parameters being a function of catchment descriptors, with a calibration emphasis on the water balance and low flows. Because of its regionalized calibration, CERF has the advantage of extending the climate range across which the parameters are evaluated, compared to the local climate within catchment-specific calibration. This is particularly important for catchments in a warming climate where evapotranspiration processes might become water limited in the future.

2.2. Risk of irrigation being constrained by volumetric abstraction license limits

2.2.1. Deriving relationships between historical annual agroclimate and irrigation licence use

Previous research has demonstrated a strong relationship between the maximum monthly Potential Soil Moisture Deficit of a given year (PSMDmax) and irrigation needs (Weatherhead and Knox, 1997; Knox et al., 2012), so that PSMDmax is used by the Environment Agency in setting volumetric limits within irrigation licences (Rees et al., 2003). It has also been used to assess climate change impacts on agricultural water requirements in the UK (Knox et al., 1997; Rey et al., 2016), Europe (Rodriguez Diaz et al., 2007) and Sri Lanka (De Silva et al., 2007). Annual PSMDmax was calculated from 1961 to 2011 using catchment-average precipitation and ETo data from both climate datasets (Met Office and FFC data) according to:

$$PSMD_{(i)} = Max\ [0, PSMD_{(i-1)} + ET_{0(i)} - P_{(i)}] \tag{1}$$

where $PSMD_{(i)}$ is the monthly Potential Soil Moisture Deficit at the end of month i (mm), $PSMD_{(i-1)}$ is the Potential Soil Moisture Deficit at the end of the previous month (i-1, mm)), $ET_{0(i)}$ is the reference evapotranspiration in month i (mm) and $P_{(i)}$ is the rainfall in month *i* (mm). In winter, precipitation generally exceeds evapotranspiration in England so PSMD is reset to zero on the 1st of January. The maximum PSMD of the 12 months of a given year is the PSMDmax.

Figure 2c shows the spatial distribution of average annual baseline PSMDmax using the observed Met Office gridded dataset. The FFC dataset captures a similar but broader range of natural climate variability than annual Maximum Potential Soil Moisture Deficit derived from observed data over the period 1961-1990, as shown in Figure S2 (supplementary material). The period 1961-1990 was selected as the baseline to be consistent with the UKCP09 (Murphy et al., 2009) and previous studies (Arnell, 2003; Johnson et al., 2009; Charlton and Arnell, 2011; Christierson et al., 2012; Hannaford and Buys, 2012)

To study the relationship between PSMDmax and surface water abstraction for irrigation, the annual PSMDmax of each year for 1999-2011 was calculated as the arithmetic average[2] of the PSMDmax for each 5km x 5km grid for each CAMS unit in England. This period corresponds to the longest within which both climatic and license abstraction data were available. Irrigation abstraction (and hence headroom) depends on climate. Thus, relationships between annual PSMDmax and the annual average licence headroom were derived by linear regressions in each CAMS unit for each headroom group over the period 1999-2011. For a small number of catchments, the correlation was not statistically significant. This could be related to growers in those catchments having high spare capacity in their licenses and thus the abstraction pattern not following changes in PSMDmax; or due

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[2] The arithmetic average was used given the uncertainty in the distribution of irrigated cropping in England.

to significant proportion of the licence holders having invested in winter storage (and associated winter abstraction licences), so that abstraction from summer surface water licences becomes largely uncoupled from the annual irrigation need determined by the PSMDmax. Only those CAMS with more than 10 licenses where the correlations were statistically significant (p value < 0.05) according to the Pearson correlation coefficient with a confidence level of 95% were subsequently used in the analysis.

2.2.2. Deriving irrigation licence usage using the Future Flows Climate dataset

The relationships between historical annual PSMDmax and the average licence headroom per headroom group and CAMS, derived from the analysis described in section 2.2.1, were applied to projected annual PSMDmax values derived from FFC for the baseline (1961-90) and future (2071-2100) periods, matching each CAMS unit with the most extensive Future Flows catchment within it. Cumulative probability distribution functions of annual headroom (considering the 11-member ensemble as a single population) for each headroom group were calculated per CAMS unit, and annual probabilities of non-exceeding 30%, 20% and 10% headroom were calculated for the baseline and future periods.

2.3. Risk of mandatory drought restrictions on surface irrigation abstraction

Under Section 57 of the Water Resources Act 1991 (Emergency variations of licences for spray irrigation purposes), the Environment Agency has the power to impose emergency restrictions on irrigation abstraction where there has been an exceptional shortage of rainfall, in order to protect the environment and public water supply. Traditionally, this type of restrictions has been only applied to surface water abstraction for irrigation. Thus, this study focuses on surface water only. Although the triggers used to define these restrictions vary slightly across the country, they are generally similar and related to hydrological low flow indicators and forecasted rainfall (Environment Agency, 2012a; 2012b; 2012c). For the purpose of this study, only the Level 1 restrictions (mandatory 50% reduction in abstraction) are considered. For Level 1 restrictions to be imposed in a catchment, river flows should be below the daily flow with an exceedance probability of 95% for that month (Q95) for 21 consecutive days; and little or no rainfall forecast. As no threshold is defined by the EA to characterize “little or no rainfall forecast”, the accumulated precipitation in 5 days that is exceeded 50% of the time (hereafter referred to as P50) was used after consultation with EA staff, to reflect higher thresholds in wetter parts of the country and the typical time limit of rainfall forecasts. P50 and monthly Q95 values were calculated for each CAMS unit for the baseline period for each of the 11 ensembles, using rainfall data from FFC and river flow data from FFH. These thresholds and rules were applied to the river flow and rainfall data for each CAMS unit for the baseline and future periods to assess the changing annual probability of a Level 1 restriction being imposed across the ensemble under baseline and future climatic conditions.

2.4. Analysing the change in surface water availability risk for irrigation

For long term farm business planning and risk management, knowledge of the probability of not being able to optimally irrigate is critical, regardless of its cause (whether from volumetric licence limits or mandatory abstraction restrictions). Thus, both risks have been combined into a single risk metric to assess how climate change will impact surface water reliability for irrigation in a particular CAMS unit. There are no standard thresholds of risk, as different farmers will have different levels of tolerable risk. Therefore, the thresholds in Table 1 were identified by expert judgement, reflecting the lower acceptable levels of risk associated with mandatory abstraction restrictions (over which farmers have no control) compared to volumetric licence limits (against which farmers can proactively modify their irrigation regimes to reduce the likelihood of running out of water).

3. Results

3.1. Effect of agroclimate on irrigation abstraction

The drier the climate, the higher the potential need for irrigation and thus the lower the licence headroom (% of unused license) will be. The relationship between climate and water abstraction is stronger for the low headroom group. The statistical significance of the correlation varies spatially, as showed in Figure 3 for the three headroom categories. For the low headroom group, correlation is significant in central and eastern England, where the number of licences (Figure 2a), volumetric surface water abstraction for irrigation (Figure 2b) and average annual PSMDmax (Figure 2c) are the greatest. However, the correlations are significant in almost all catchments in which there are at least 10 surface water irrigation licences (see Tables S1-S3 in the supplementary material for a full description of the regression coefficients). Figure 4a shows an example of the linear regressions obtained in the Broadland Rivers CAMS for each headroom group, located in eastern England.

3.2. Current and future risk of sub-optimal irrigation due to volumetric surface water abstraction licence limits

Across England, licence headroom is projected to be lower in the future period as increasing aridity (PSMDmax) lead to increased irrigation needs and hence abstraction. The greatest impacts affect the low headroom group. As an example, Figure 4b shows the current and future cumulative probability distribution of annual headroom for each group for the Broadland Rivers CAMS, where the annual probability of using 80% of the licensed volumetric limit (i.e., probability of having 20% headroom) rises from 0.23 for the baseline (1961-1990) to 0.72 in the future (2071-2098) for the low headroom group. Figure 5a shows the current and future probability of using more than 80% of the licensed volumetric limit. In the future, this is projected to exceed 0.7 in the low headroom group in 45% of the 45 CAMS units analysed. Results are also presented in Figure S3 for 10% and 30% headroom to demonstrate the limited sensitivity of the spatial patterns to the chosen threshold, whilst Table 2 shows the number of CAMS where the probability of having less than 30, 20 and 10% headroom is expected to exceed 0.5 and 0.7 in the low headroom group.

In general, the risk of using a high proportion of the licensed volumetric limit, and therefore having low headroom, is greatest in central and eastern England, where most irrigated agriculture is currently located. In the west and in the north, the current lower risk is a consequence of low irrigation demand due to higher precipitation and lower evapotranspiration. However, the results show significant future headroom reductions in these areas due to higher PSMDmax, with almost all CAMS units having a future annual probability of using more than 80% of the licensed volumetric limit of greater than 0.2.

3.3. Risk of mandatory drought restrictions on abstraction for irrigation

Figure 5b shows the annual probability of mandatory Level 1 restrictions being imposed on surface water abstraction for irrigation for the baseline and future periods. Although this annual probability does not exceed 0.05 in the baseline period, it is projected to increase in all catchments in the future. However, in contrast to the spatial changes in the analysis of licence headroom (Figure 5a), the increase in the annual risk of mandatory drought restrictions is higher in the northwest, west and southwest, reaching up to 0.3 in some CAMS in the future. Irrigators within the medium and high headroom categories will be similarly exposed to the risk of abstraction restrictions as these drought management rules apply equally to all surface water irrigators.

3.4. Combined risk of abstraction licensing limits and restrictions

Figure 5c shows the changes in the combined risk of not having access to sufficient water for irrigation in a given year for the low headroom group, either because of the volumetric limits on each surface water abstraction licence or because of mandatory abstraction restrictions being imposed during the irrigation season. Having Level 1 restrictions imposed during the baseline period (1961-1990) has a low probability and thus the risk to irrigators is principally due to volumetric licence limits, notably in the east and south east which are the most agriculturally productive regions. Although aridity is expected to increase everywhere in the country, these areas are also projected to remain the driest parts of England and will be exposed to the highest risk over the period 2071-2098. In contrast, western England and parts of the south west are projected to be at most risk of being constrained by mandatory abstraction restrictions in the future. For the medium and the high headroom groups, the risk of running out of water for irrigation is relatively low as they have spare capacity, even though licence use is expected to increase for all headroom groups but are equally at risk from mandatory abstraction restrictions in the future.

4. Discussion

This study analyses the impact of climate change on future surface water availability risks for irrigated agriculture in England, focusing on both volumetric limits on individual abstraction licences and mandatory abstraction restrictions imposed at the catchment-scale by the water regulator. Our results show a general increase in irrigation abstraction (expressed as a decrease in the licence headroom) in the future (2071-2098) in response to greater aridity, consistent with previous studies for the UK (Weatherhead and Knox 1997; Weatherhead and Knox, 2000; HR Wallington, 2012; Weatherhead et al., 2015). However, these studies assumed that irrigation is unconstrained at both licence and catchment scales. This paper presents the first attempt to provide a risk-based assessment of the future probability of irrigators being constrained by the abstraction licensing system and/or mandatory surface water abstraction restrictions during drought.

Irrigators in the medium and low headroom groups are shown to be the most affected by the projected change in climate, as they are already abstracting a significant part of their licensed volume in most dry years. However, there are many other factors that would influence abstraction for irrigation purposes, such as crop type, irrigated area, yield and quality standards imposed by retailers and water-saving strategies. Increasing summer aridity will lead to increasing risks of their abstraction being curtailed due to volumetric licence limits, with greater economic impact in the highly productive irrigated areas in eastern and southern England (Rey et al., 2016), where Vasileiou et al. (2014) showed that a 10% reduction in water use due to abstraction limitations in eastern England leads to an average 6% fall in net margin. In contrast, the high headroom group which represents those farmers who abstract a low proportion of their licence (due to growing a relatively small irrigated crop area in comparison to their licence volume) will be largely unaffected by the direct impacts of climate change on irrigation need, unless their licenses are revised as part of the abstraction reform plan.

In contrast, all surface water licences in all CAMS units are projected to have a higher risks of being under mandatory 50% (Level 1) abstraction restrictions in the future period due to reduced summer low river flows, but especially in northern and western England. Although these regions are wetter than the south and east of the country, the river flows are more sensitive to drought as groundwater contributes less baseflow to sustain river flows during low rainfall periods due to the soil and geological characteristics of those regions

The results therefore show that the underlying drivers of increased future risk of constraint on surface water abstraction for irrigation differ in space (due to spatial differences in climate and hydrogeology) and between irrigators (due to differences in attitudes to risk and availability of land that manifest in differences in headroom). However, it is acknowledged that there are limitations to this study that arise due to the design of the FutureFlows project (and associated datasets) and due to lack of data.

Firstly, the difficulties of simulating river discharges during extreme events such as droughts are well recognized. Although the simulated river discharge within the Future Flows Hydrology dataset typically show the largest departures from observed river discharge during dry conditions and in drier regions, this is mainly attributed to climate rather than hydrological modelling uncertainty. As no systematic bias was identified in FFH and following common practice, it is assumed here that the modelled signal of hydrological change is attributable to the climate change and does not contain any systematic bias (Prudhomme et al., 2012a). In addition, the distribution of changes in low flow in FFH has been shown to cover most of the spread obtained from using the UKCP09 climate change factors (Prudhomme et al., 2012a). These were designed to capture most of the climate model structure and parameter uncertainty, and are still the most comprehensive to date for the UK.

Secondly, the FFC and FFH results used in this study are based on the SRES A1B emissions scenarios (IPCC, 2000), a plausible but not extreme view of possible future conditions. The evolution of atmospheric greenhouse gas concentrations in these scenarios is broadly similar to the Representative Concentration Profile (RCP) 6.0 (Melillo et al., 2014). We recognize that using different emissions scenarios or RCPs might give more optimistic (based on the Paris accord and RCP 2.8 or 4.0) or pessimistic (based on current emissions trajectories and RCP8.5) results.

Finally, our derived relationships between the annual indictor of aridity (PSMDmax) and surface water irrigation abstraction (expressed as annual licence headroom) assumes that the cropped area, crop mix and irrigation technologies used within each headroom group in each CAMS unit remain constant, due to the lack of spatial baseline data on irrigated cropping distribution and the associated abstraction licences. Future land use change projections are highly complex and subject to a high degree of uncertainty (Holman et al., 2017). Previous landuse change modelling studies have demonstrated the importance of future socioeconomic conditions and cross-sectoral interactions as drivers for change in the agricultural sector, in combination with climatic conditions (Harrison et al., 2015). However, these studies did not distinguish between irrigated and rainfed cropping or assess how the distribution of crops such as vegetables and soft fruit will change in the UK in the future. Regarding irrigation technologies, changes in irrigation efficiency in England are likely to be relatively unimportant given the current high efficiency of irrigation due to the high capital and operating costs that growers face. Similarly, as irrigation in the UK is supplemental to rainfall and focused primarily on delivering high-quality produce, it is unlikely that growers will switch to drought resistant varieties unless they can match food quality requirements.

Nevertheless, growers are likely to autonomously adapt to changing conditions. Consequently, we have deliberately studied the future risk of having insufficient licensed water separately from the risk of abstraction restrictions in a given year as their implications and available management options at the farm level are very different. In the case of an abstractor getting close to their abstraction licence limit, this has a relatively long lead time and the farm business can adapt their activity to reduce the financial impacts. Such adaptation can be anticipatory (long-term planning), such as investing in on-farm storage and/or more efficient irrigation systems (Knox and Weatherhead 2005; Daccache et al., 2015), seeking other alternative water sources (if available) or changing the crop mix and/or the irrigated area. It can also be re-active (short-term adaptation), giving priority in that season to high value crops or seeking to obtain additional resources through water trading (Fereres and Soriano, 2007; Iglesias et al., 2009; Kahil et al., 2015; Rey et al., 2015). In contrast, mandatory abstraction restrictions imposed by the regulator during a drought period may have little forewarning and an unknown duration, providing limited coping strategies for those farmers without an on-farm reservoir. The economic consequences of such restrictions regarding crop yield and quality can be very severe (Rey et al., 2016). That is why irrigators in some areas of eastern England agreed on early voluntary abstraction restrictions during the last drought (2010-2012) to avoid mandatory ones later in the season (Rey et al., 2017).

As water availability risks increase in the future, abstraction management strategies will need to evolve to meet competing needs in the face of expected increased climatic variability whilst minimizing adverse economic impacts (Holman and Trawick, 2011). Making the most of available water resources will become increasingly important through, for example, providing flexibility to abstract water for on-farm reservoirs during summer runoff events; re-allocating water held within unused or partly used abstraction licences in dry years and enhancing water trading to release this potential, hence promoting both economic and water use efficiency (Möller-Gulland, 2010; Rey, 2014); and strategic water transfers from wetter to drier areas (Gupta and Van der Zaag, 2008; Water UK, 2016). These may require a more collaborative approach to water management between abstractors and environmental regulators and a greater role for Water Abstractor Groups (Leathes et al., 2008; Whaley and Weatherhead, 2015a; Whaley and Weatherhead, 2015b). The outcomes of this first national assessment of climate change impacts on supplemental irrigation water availability risks highlights the importance of developing such collaborative approaches to reduce future impacts whilst balancing competing demands and food security.

5. Conclusion

In Europe, climate change is expected to increase temperatures, modify rainfall patterns, intensify drought frequency and severity, and lead to increased crop water demand. Consequently, supplemental irrigation is likely to become more important to agriculture to maintain crop yields and quality in currently humid climates, but abstraction is likely to face increasing risk of being constrained during droughts to protect the environment and public water supply. This study presents the first risk-based assessment of the future annual probability of irrigators being unable to irrigate optimally due to the constraints of an abstraction licensing system and/or mandatory abstraction restrictions during drought in England. The results show that the causes of increased risk differ spatially, with future constraints from volumetric abstraction licence limits becoming more important in the drier parts of the country in the east England, and mandatory abstraction restrictions due to future low river levels during droughts becoming more frequent in the north and west due to the reduced buffering effect of baseflow from groundwater.

Based on our results, the increase in water availability risks for irrigation in the coming decades will pose a significant challenge for the sector. This highlights the importance of agricultural adaptation strategies and demonstrates the increasing need for collaborative working between growers and the regulator to ensure water related risks are minimized and the negative consequences of drought management actions (e.g., abstraction restrictions) are mitigated..

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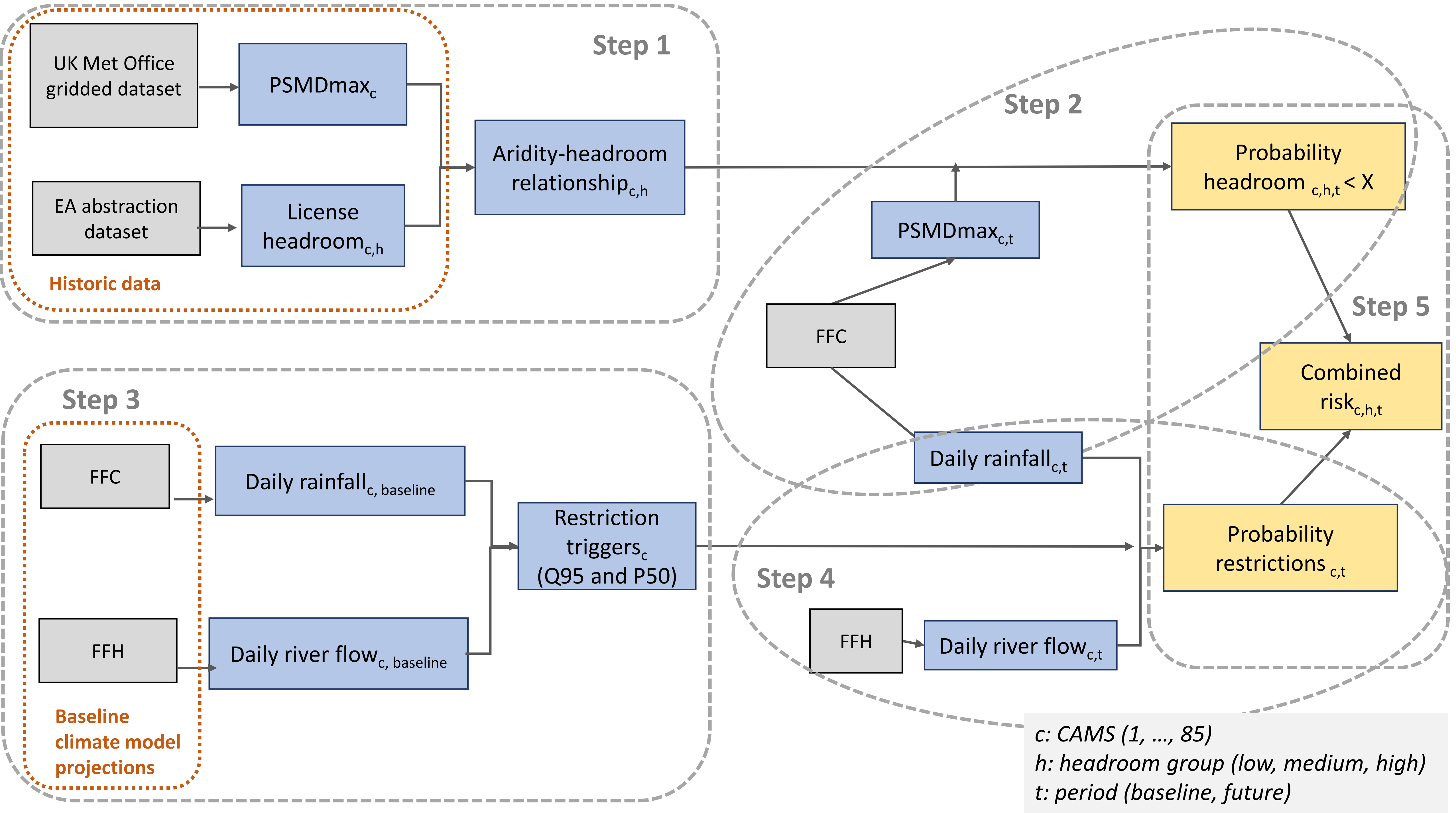
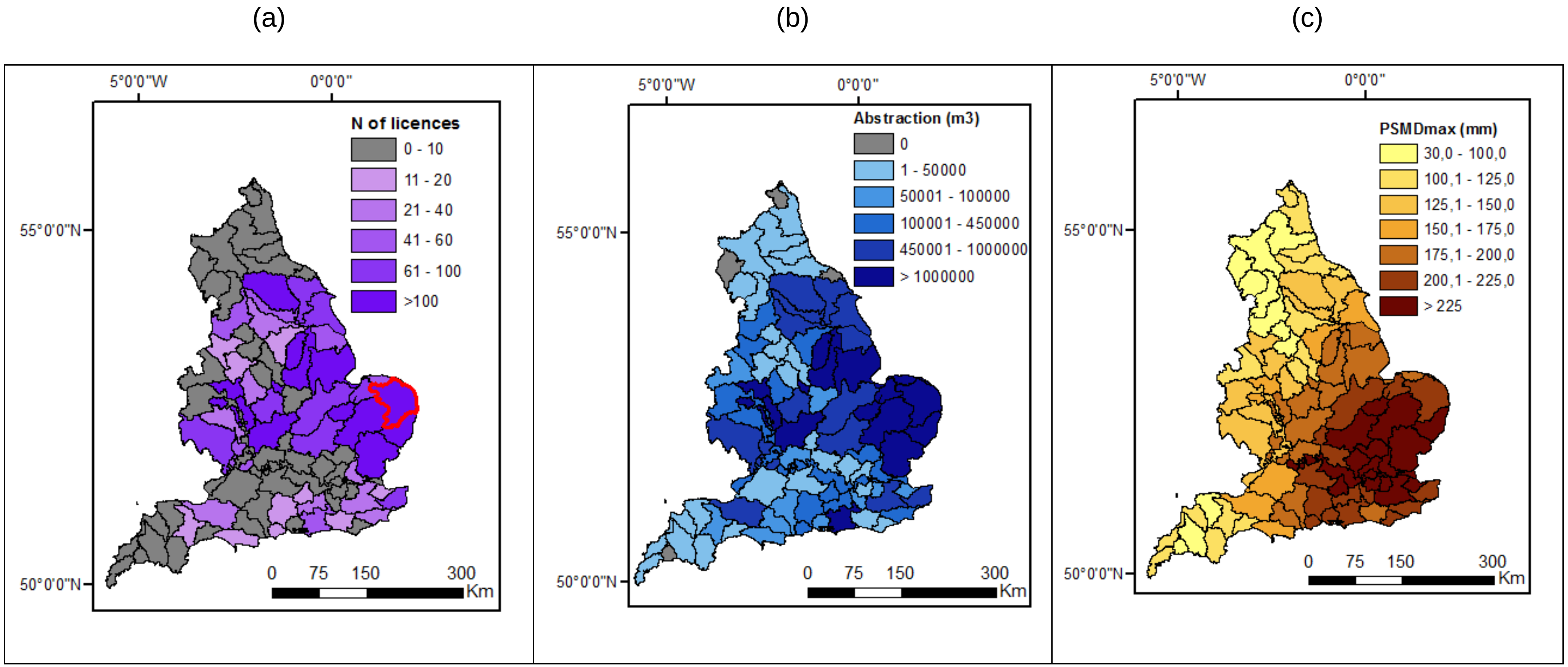
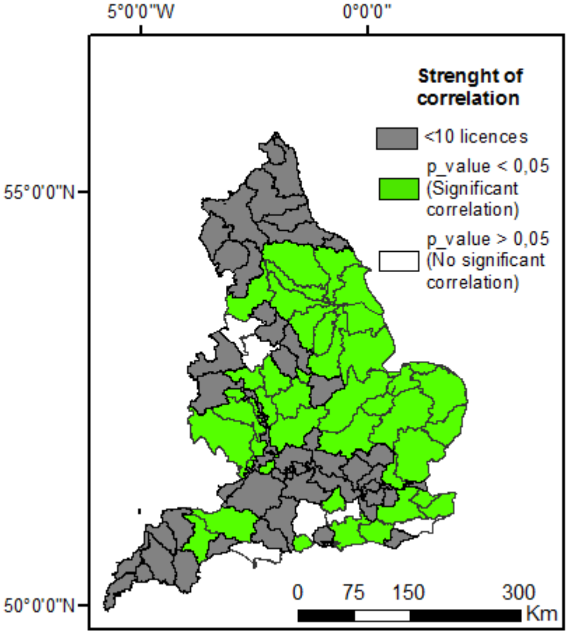
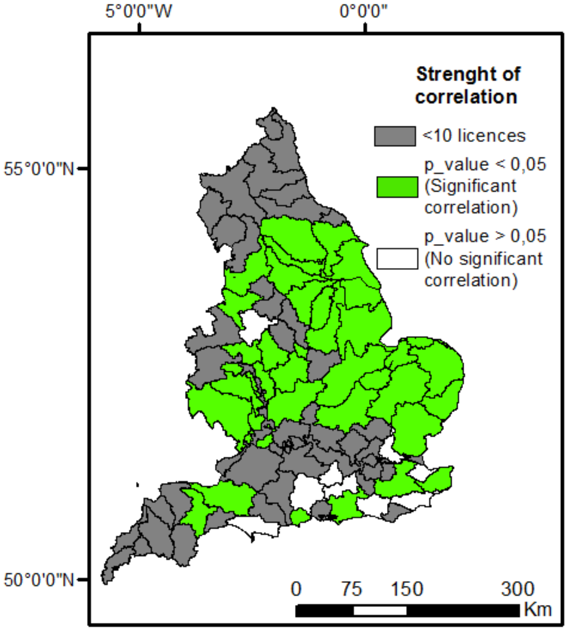

Step 1
UK Met Office gridded dataset
PSMDmax$_{c}$
EA abstraction dataset
License headroom$_{c,h}$
Aridity-headroom relationship$_{c,h}$
Historic data
Step 2
PSMDmax$_{c,t}$
FFC
Daily rainfall$_{c,t}$
Step 5
Probability headroom $_{c,h,t}$ < X
Combined risk$_{c,h,t}$
Probability restrictions $_{c,t}$
Step 3
FFC
Daily rainfall$_{c,\ \text{baseline}}$
FFH
Daily river flow$_{c,\ \text{baseline}}$
Restriction triggers$_{c}$ (Q95 and P50)
Baseline climate model projections
Step 4
FFH
Daily river flow$_{c,t}$
c: CAMS (1, …, 85)
h: headroom group (low, medium, high)
t: period (baseline, future)


(a)
(b)
(c)
5°0'0"W
0°0'0"
55°0'0"N
50°0'0"N
N of licences
0 - 10
11 - 20
21 - 40
41 - 60
61 - 100
>100
0
75
150
300
Km
Abstraction (m3)
0
1 - 50000
50001 - 100000
100001 - 450000
450001 - 1000000
> 1000000
PSMDmax (mm)
30,0 - 100,0
100,1 - 125,0
125,1 - 150,0
150,1 - 175,0
175,1 - 200,0
200,1 - 225,0
> 225

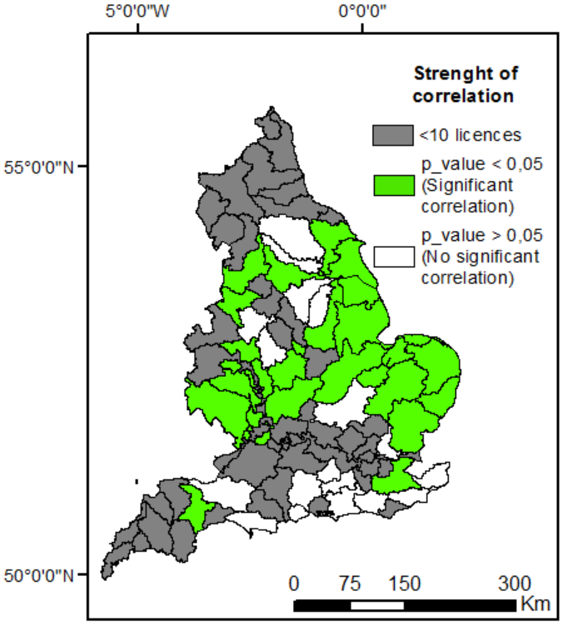
Low headroom

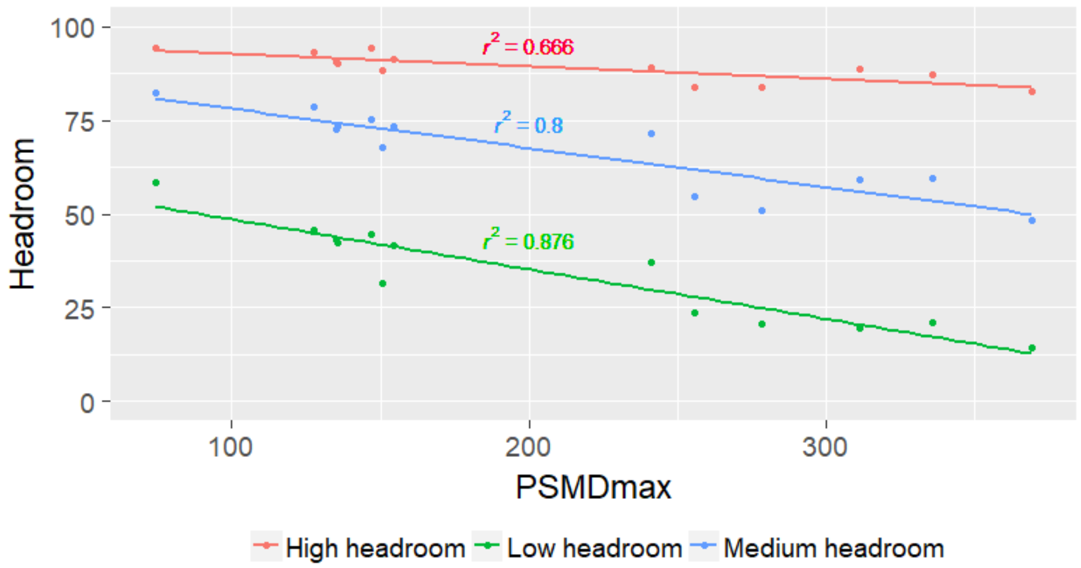


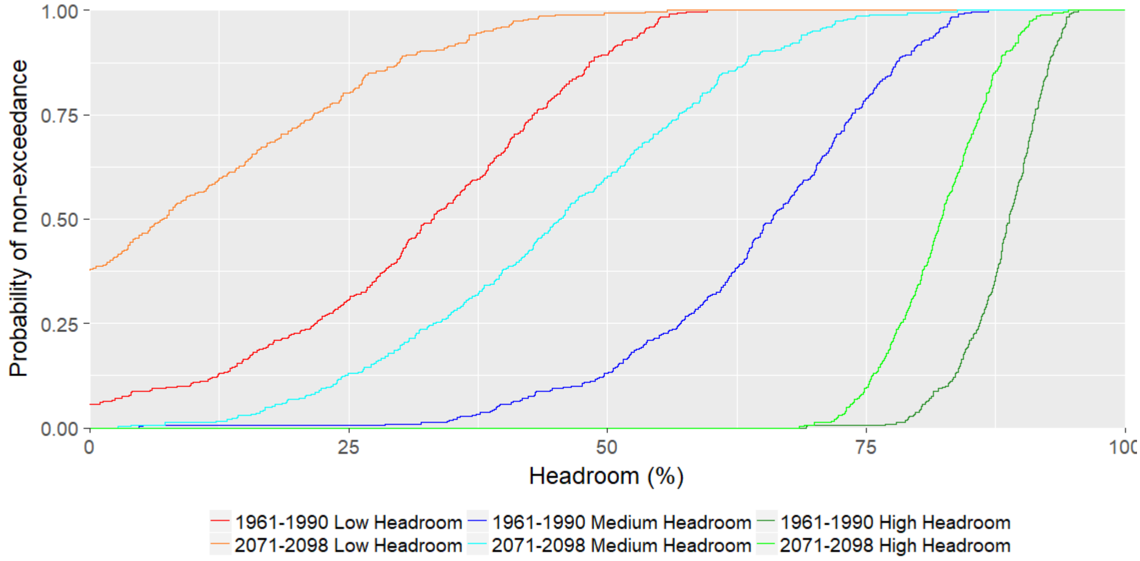
Medium headroom



High headroom




100
75
50
25
0
Headroom
$r^2 = 0.666$
$r^2 = 0.8$
$r^2 = 0.876$
100
200
300
PSMDmax
High headroom
Low headroom
Medium headroom


1.00
0.75
0.50
0.25
0.00
Probability of non-exceedance
0
25
50
75
10
Headroom (%)
1961-1990 Low Headroom
1961-1990 Medium Headroom
1961-1990 High Headroom
2071-2098 Low Headroom
2071-2098 Medium Headroom
2071-2098 High Headroom

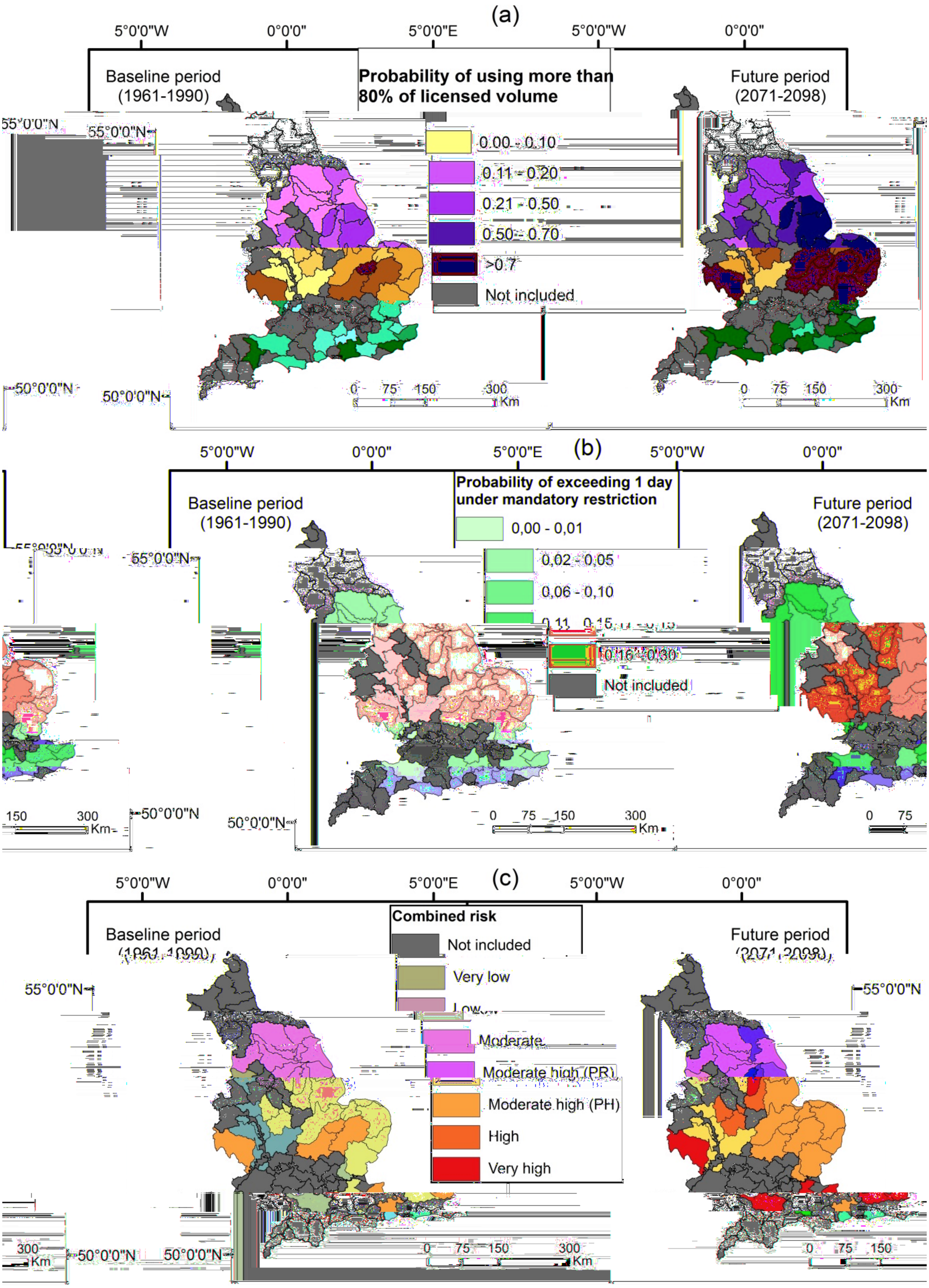

(a)
5°0'0"W
0°0'0"
5°0'0"E
Baseline period (1961-1990)
Future period (2071-2098)
Probability of using more than 80% of licensed volume
0.00 - 0.10
0.11 - 0.20
0.21 - 0.50
0.50 - 0.70
>0.7
Not included
55°0'0"N
50°0'0"N
0 75 150 300 Km
(b)
Probability of exceeding 1 day under mandatory restriction
0,00 - 0,01
0,02 - 0,05
0,06 - 0,10
0,11 - 0,15
0,16 - 0,30
Not included
(c)
Combined risk
Not included
Very low
Low
Moderate
Moderate high (PR)
Moderate high (PH)
High
Very high

Figure captions

Figure 1. Methodological diagram

Figure 2. (a) Number of summer surface water abstraction licenses for irrigation (Broadland Rivers CAMS highlighted in red); (b) Average annual summer surface water abstraction for irrigation over the period 1999-20111; (c) Average PSMDmax from 1999 to 2011;

Figure 3. Statistical significance of the correlation between annual PSMDmax and license headroom for the low (a), medium (b) and high (c) headroom group.

Figure 4. Example results of (a) the explanatory relationship between annual PSMDmax (mm) and historical license use (headroom, %) for the three headroom groups and (b) the cumulative probability distribution of headroom for the baseline (1961-90) and future (2071-2098) periods for the Broadland Rivers CAMS.

Figure 5. Comparison of (a) the annual probability of falling below 20% headroom in the low headroom group ; (b) the annual probability of being under mandatory abstraction restrictions during the irrigation season; and (c) the combined risk classes of being unable to optimally irrigate due to either factor between baseline (1961-90) and future (2071-2098) periods.

Table 1. Combined risk categories based on joint probabilities of license headroom constraints and mandatory abstraction restrictions

Combined risk	**Annual probability of headroom < 20% (PH)**	**Annual probability of mandatory abstraction restrictions (PR)**
Very high	$PH \geq 0.7$	$PR \geq 0.10$
High	$0.5 \leq PH < 0.7$	$PR \geq 0.10$
Moderate-High (PH)	$PH \geq 0.5$	$PR < 0.10$
Moderate-High (PR)	$PH \leq 0.5$	$PR > 0.10$
Moderate	$PH < 0.5$	$0.01 \leq PR \leq 0.10$
Low	$0.2 < PH \leq 0.5$	$PR \leq 0.01$
Very low	$PH \leq 0.2$	$PR \leq 0.01$

Table 2. Probability of running out of water for irrigation in the low headroom group in the baseline and future periods. Number of CAMS exceeding the headroom threshold.

Headroom	**Annual probability of exceeding the threshold**	**1961-1990**		**2071-2098**	
		Number of CAMS	**%**	**Number of CAMS**	**%**
30%	> 0.5	14	33%	33	79%
	> 0.7	9	21%	24	57%
20%	> 0.5	6	14%	27	64%
	> 0.7	2	5%	19	45%
10%	> 0.5	1	2%	18	43%
	> 0.7	0	0%	12	29%