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

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13 **Abstract**

14 In many temperate parts of the world, supplemental irrigation is crucial to assure both crop
15 yield and quality. Climate change could increase the risks of irrigation being restricted by
16 increasing crop water requirements and/or decreasing water availability. In England, water
17 abstraction for irrigation is limited by maximum annual volumetric limits, as specified in the
18 abstraction licenses, and surface water abstraction restrictions imposed by the regulator
19 during drought. This paper assesses how climate change might impact future irrigation
20 abstraction reliability from surface water in England. Firstly, the probability of annual
21 abstraction being close to the maximum license limit was estimated for the baseline (1961-
22 1990) and future (2071-2098) periods in each catchment based on observed relationships

23 between annual weather and irrigation abstraction in three licence usage groups. Secondly,
24 the current river discharge triggers for mandatory drought restrictions were used to assess the
25 annual probability of surface water abstraction restrictions being imposed by the regulator in
26 each period. Results indicate significant future increases in irrigated abstraction license use
27 due to an increase in aridity, particularly in the most productive agricultural areas located in
28 eastern and southern England, assuming no adaptation. The annual probability of having less
29 than 20% licence headroom in the highest usage group is projected to exceed 0.7 in 45% of
30 the management units, mostly in the south and east. In contrast, irrigators in central and
31 western England face an increased risk of drought restrictions due to the lower buffering
32 capacity of groundwater on river flows, with the annual probability of mandatory drought
33 restrictions reaching up to 0.3 in the future. Our results highlight the increasing abstraction
34 reliability risks for irrigators due to climate change, and the need for the farming community
35 and the regulator to adapt and collaborate to mitigate the associated impacts.

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

37 **1. Introduction**

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

46 change and competing demands for water (FAO, 2002; De Silva et al., 2007; Rodriguez Diaz
47 et al., 2007; Charlton and Arnell, 2011; Gerten et al., 2011).

48 This tri-lemma of reduced water resource availability, increased irrigation demand
49 and increasing competition between water users will require regulatory bodies to actively
50 manage abstraction to ensure water resources sustainability and environmental protection
51 (Henriques et al., 2008; Weatherhead and Howden, 2009). In Europe, governments have their
52 own national legislation and abstraction management rules, described by Mills and Dwyer
53 (2009), in addition to European regulations. For example, financial charges are payable in
54 Germany according to the volume of water abstracted; France also applies volumetric charges
55 and water users require a permit to abstract more than 8m³/h; similarly, Denmark uses a time-
56 limited permit system for ground and surface water abstraction; and Belgium, Netherlands
57 and the United Kingdom have compulsory registration and licensing systems, in which
58 abstraction can be restricted during severe droughts.

59 In England, an abstraction licence is required from the Environment Agency (EA) to
60 abstract more than 20 m³/day from surface or groundwater (Environment Agency, 2013).
61 However, having an irrigation abstraction licence does not entitle the licence holder to always
62 be able to abstract, as the EA can impose partial or total bans on irrigation abstraction from
63 surface water sources during droughts to protect public water supplies and the aquatic
64 environment (Environment Agency, 2015). Such restrictions on supplemental irrigation can
65 have severe impacts on crop yield and quality leading to considerable financial losses - Rey
66 et al. (2016) assessed the net financial benefits of supplemental agricultural irrigation at the
67 farm level in a dry year at over £660 million in England and Wales, using current irrigated
68 cropping and market data. Irrigation is mainly concentrated in central and eastern England,
69 where many catchments are already assessed by the EA as “over-abstracted” or “over-
70 licensed” (Hess et al., 2011) and therefore vulnerable to future pressures on water resources.

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

80 **2. Material and methods**

81 There are five main stages to the analysis (Figure 1). Firstly, explanatory
82 relationships between actual annual licence usage by irrigators in the period 1999-2011 and
83 an annual agroclimatic indicator of aridity (annual maximum Potential Soil Moisture Deficit,
84 PSMD) are derived from observed data for each of the 85 Catchment Abstraction
85 Management Strategy (CAMS) units in England (Step 1). Secondly, the relationships
86 obtained in Step 1 are applied to baseline (1961-1990) and future (2071-2100) annual
87 PSMDmax calculated from (FFC) (Step 2), assuming stationarity in crop spatial distribution
88 and irrigation efficiency, to estimate the annual probability of irrigators in each CAMS being
89 constrained by the volumetric abstraction license limit for each period. Thirdly, the drought
90 management rules currently used by the Environment Agency are applied to the simulated
91 timeseries of daily river flow and rainfall data for the baseline period (1961-90) from the
92 Future Flows Climate (FFC) and Future Flows Hydrology (FFH) datasets, respectively, to
93 calculate the daily river flow and rainfall triggers for mandatory restrictions on irrigation
94 abstraction (Step 3). Fourthly, the restriction triggers in Step 3 are applied to simulated
95 baseline and future (2071-2100) daily river flows (FFH) and rainfall (FFC) to estimate the

96 annual probability of irrigators in each CAMS being under mandatory drought restrictions
97 (Step 4). Finally, a combined risk metric was calculated based on the results from Steps 2 and
98 4, representing the annual probability for irrigators being close to their volumetric license
99 limit and being under mandatory drought abstraction restriction (Step 5). Results from the
100 baseline and future periods were then compared to assess the direct and indirect climate
101 change impact on surface water reliability for irrigation in every catchment across England.

102 2.1. Data

103 2.1.1. Climate data

104 Two sets of climate data are used: i) a 5km x 5km UK Meteorological Office gridded
105 dataset of observed monthly precipitation and derived reference evapotranspiration estimated
106 using the FAO Penman-Monteith equation (Allen et al., 1998) from 1961 to 2011; ii) the
107 Future Flows Climate (FFC) dataset (Prudhomme et al., 2012b), a national-scale set of high
108 resolution transient climate change projections of precipitation and reference
109 evapotranspiration for 1950 to 2098 based on 11 different variants of a regional climate
110 model, that captures climate modelling uncertainty. This 11-member ensemble is based on
111 HadRM3-PPE (Met Office Hadley Centre's Regional Climate Model Perturbed Physics
112 Ensemble) under the SRES A1B emissions scenario (Special Report on Emissions Scenarios;
113 IPCC, 2000), which was used as part of the derivation of the current (UKCP09) scenarios¹
114 (Murphy et al., 2009).

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

¹ A1B is broadly similar to the Representative Concentration Profile (RCP) 6.0 (Melillo et al., 2014).

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

125 2.1.2. Irrigation abstraction data

126 The annual volumetric licence limit and actual monthly abstraction for the period
127 1999-2011 for 3,738 groundwater and surface water summer abstraction licences for
128 irrigation in England were obtained from the Environment Agency (EA) for the 85 CAMS
129 units, which are the spatial units by which the EA manages water resources (Environment
130 Agency, 2013). For the purpose of this paper, only CAMS having at least 10 surface water
131 irrigation licences were included in the analysis (Figure 2a). The focus is on surface water
132 licences only, as groundwater abstraction is not affected by mandatory abstraction restrictions
133 in drought periods. Although the split between surface water and groundwater abstraction
134 varies considerably between catchments (Figure S1 from the Supplementary Material),
135 abstraction from surface water for irrigation is significant (Figure 2b)- in the most recent
136 drought year (2011), more than 50% of total abstraction for spray irrigation in England was
137 from surface water.

138 The EA abstraction dataset does not provide any information on associated irrigated
139 crop types or irrigated areas for each license. Furthermore, no datasets exist on the spatial
140 distribution of irrigated crops in the country, so it is not possible to project licence-specific
141 annual volumetric irrigation need (Rees et al., 2003). However, according to the latest

142 irrigation survey (Defra, 2011), potatoes represent more than 40% of the total irrigated area in
143 England, followed by vegetables (24%).

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

162 2.1.3. Hydrological data

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

166 (Continuous Estimation of River Flows) regionalized rainfall-runoff model (Griffiths et al.,
167 2006), containing 85 catchments across England and Wales, was used here. CERF was
168 calibrated across all catchments simultaneously to obtain a best model fit across all
169 catchments, with model parameters being a function of catchment descriptors, with a
170 calibration emphasis on the water balance and low flows. Because of its regionalized
171 calibration, CERF has the advantage of extending the climate range across which the
172 parameters are evaluated, compared to the local climate within catchment-specific
173 calibration. This is particularly important for catchments in a warming climate where
174 evapotranspiration processes might become water limited in the future.

175 2.2. Risk of irrigation being constrained by volumetric abstraction license limits

176 2.2.1. Deriving relationships between historical annual agroclimate and irrigation
177 licence use

178 Previous research has demonstrated a strong relationship between the maximum
179 monthly Potential Soil Moisture Deficit of a given year (PSMD_{max}) and irrigation needs
180 (Weatherhead and Knox, 1997; Knox et al., 2012), so that PSMD_{max} is used by the
181 Environment Agency in setting volumetric limits within irrigation licences (Rees et al.,
182 2003). It has also been used to assess climate change impacts on agricultural water
183 requirements in the UK (Knox et al., 1997; Rey et al., 2016), Europe (Rodriguez Diaz et al.,
184 2007) and Sri Lanka (De Silva et al., 2007). Annual PSMD_{max} was calculated from 1961 to
185 2011 using catchment-average precipitation and ETo data from both climate datasets (Met
186 Office and FFC data) according to:

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

187 where $PSMD_{(i)}$ is the monthly Potential Soil Moisture Deficit at the end of month i (mm),
188 $PSMD_{(i-1)}$ is the Potential Soil Moisture Deficit at the end of the previous month ($i-1$, mm)),
189 $ET_{0(i)}$ is the reference evapotranspiration in month i (mm) and $P_{(i)}$ is the rainfall in month i
190 (mm). In winter, precipitation generally exceeds evapotranspiration in England so PSMD is
191 reset to zero on the 1st of January. The maximum PSMD of the 12 months of a given year is
192 the PSMDmax.

193 Figure 2c shows the spatial distribution of average annual baseline PSMDmax using
194 the observed Met Office gridded dataset. The FFC dataset captures a similar but broader
195 range of natural climate variability than annual Maximum Potential Soil Moisture Deficit
196 derived from observed data over the period 1961-1990, as shown in Figure S2
197 (supplementary material). The period 1961-1990 was selected as the baseline to be consistent
198 with the UKCP09 (Murphy et al., 2009) and previous studies (Arnell, 2003; Johnson et al.,
199 2009; Charlton and Arnell, 2011; Christerson et al., 2012; Hannaford and Buys, 2012)

200 To study the relationship between PSMDmax and surface water abstraction for
201 irrigation, the annual PSMDmax of each year for 1999-2011 was calculated as the arithmetic
202 average² of the PSMDmax for each 5km x 5km grid for each CAMS unit in England. This
203 period corresponds to the longest within which both climatic and licence abstraction data
204 were available. Irrigation abstraction (and hence headroom) depends on climate. Thus,
205 relationships between annual PSMDmax and the annual average licence headroom were
206 derived by linear regressions in each CAMS unit for each headroom group over the period
207 1999-2011. For a small number of catchments, the correlation was not statistically
208 significant. This could be related to growers in those catchments having high spare capacity
209 in their licenses and thus the abstraction pattern not following changes in PSMDmax; or due

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

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

216 2.2.2. Deriving irrigation licence usage using the Future Flows Climate dataset

217 The relationships between historical annual PSMDmax and the average licence
218 headroom per headroom group and CAMS, derived from the analysis described in section
219 2.2.1, were applied to projected annual PSMDmax values derived from FFC for the baseline
220 (1961-90) and future (2071-2100) periods, matching each CAMS unit with the most
221 extensive Future Flows catchment within it. Cumulative probability distribution functions of
222 annual headroom (considering the 11-member ensemble as a single population) for each
223 headroom group were calculated per CAMS unit, and annual probabilities of non-exceeding
224 30%, 20% and 10% headroom were calculated for the baseline and future periods.

225 2.3. Risk of mandatory drought restrictions on surface irrigation abstraction

226 Under Section 57 of the Water Resources Act 1991 (Emergency variations of licences
227 for spray irrigation purposes), the Environment Agency has the power to impose emergency
228 restrictions on irrigation abstraction where there has been an exceptional shortage of rainfall,
229 in order to protect the environment and public water supply. Traditionally, this type of
230 restrictions has been only applied to surface water abstraction for irrigation. Thus, this study
231 focuses on surface water only. Although the triggers used to define these restrictions vary
232 slightly across the country, they are generally similar and related to hydrological low flow
233 indicators and forecasted rainfall (Environment Agency, 2012a; 2012b; 2012c). For the

234 purpose of this study, only the Level 1 restrictions (mandatory 50% reduction in abstraction)
235 are considered. For Level 1 restrictions to be imposed in a catchment, river flows should be
236 below the daily flow with an exceedance probability of 95% for that month (Q95) for 21
237 consecutive days; and little or no rainfall forecast. As no threshold is defined by the EA to
238 characterize “little or no rainfall forecast”, the accumulated precipitation in 5 days that is
239 exceeded 50% of the time (hereafter referred to as P50) was used after consultation with EA
240 staff, to reflect higher thresholds in wetter parts of the country and the typical time limit of
241 rainfall forecasts. P50 and monthly Q95 values were calculated for each CAMS unit for the
242 baseline period for each of the 11 ensembles, using rainfall data from FFC and river flow data
243 from FFH. These thresholds and rules were applied to the river flow and rainfall data for each
244 CAMS unit for the baseline and future periods to assess the changing annual probability of a
245 Level 1 restriction being imposed across the ensemble under baseline and future climatic
246 conditions.

247 2.4. Analysing the change in surface water availability risk for irrigation

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

258 3. Results

259 3.1. Effect of agroclimate on irrigation abstraction

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

271 3.2. Current and future risk of sub-optimal irrigation due to volumetric surface 272 water abstraction licence limits

273 Across England, licence headroom is projected to be lower in the future period as
274 increasing aridity (PSMDmax) lead to increased irrigation needs and hence abstraction. The
275 greatest impacts affect the low headroom group. As an example, Figure 4b shows the current
276 and future cumulative probability distribution of annual headroom for each group for the
277 Broadland Rivers CAMS, where the annual probability of using 80% of the licensed
278 volumetric limit (i.e., probability of having 20% headroom) rises from 0.23 for the baseline
279 (1961-1990) to 0.72 in the future (2071-2098) for the low headroom group. Figure 5a shows
280 the current and future probability of using more than 80% of the licensed volumetric limit. In
281 the future, this is projected to exceed 0.7 in the low headroom group in 45% of the 45 CAMS

282 units analysed. Results are also presented in Figure S3 for 10% and 30% headroom to
283 demonstrate the limited sensitivity of the spatial patterns to the chosen threshold, whilst Table
284 2 shows the number of CAMS where the probability of having less than 30, 20 and 10%
285 headroom is expected to exceed 0.5 and 0.7 in the low headroom group.

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

293 3.3. Risk of mandatory drought restrictions on abstraction for irrigation

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

303 3.4. Combined risk of abstraction licensing limits and restrictions

304 Figure 5c shows the changes in the combined risk of not having access to sufficient
305 water for irrigation in a given year for the low headroom group, either because of the

306 volumetric limits on each surface water abstraction licence or because of mandatory
307 abstraction restrictions being imposed during the irrigation season. Having Level 1
308 restrictions imposed during the baseline period (1961-1990) has a low probability and thus
309 the risk to irrigators is principally due to volumetric licence limits, notably in the east and
310 south east which are the most agriculturally productive regions. Although aridity is expected
311 to increase everywhere in the country, these areas are also projected to remain the driest parts
312 of England and will be exposed to the highest risk over the period 2071-2098. In contrast,
313 western England and parts of the south west are projected to be at most risk of being
314 constrained by mandatory abstraction restrictions in the future. For the medium and the high
315 headroom groups, the risk of running out of water for irrigation is relatively low as they have
316 spare capacity, even though licence use is expected to increase for all headroom groups but
317 are equally at risk from mandatory abstraction restrictions in the future.

318 **4. Discussion**

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

330 Irrigators in the medium and low headroom groups are shown to be the most affected
331 by the projected change in climate, as they are already abstracting a significant part of their
332 licensed volume in most dry years. However, there are many other factors that would
333 influence abstraction for irrigation purposes, such as crop type, irrigated area, yield and
334 quality standards imposed by retailers and water-saving strategies. Increasing summer aridity
335 will lead to increasing risks of their abstraction being curtailed due to volumetric licence
336 limits, with greater economic impact in the highly productive irrigated areas in eastern and
337 southern England (Rey et al., 2016), where Vasileiou et al. (2014) showed that a 10%
338 reduction in water use due to abstraction limitations in eastern England leads to an average
339 6% fall in net margin. In contrast, the high headroom group which represents those farmers
340 who abstract a low proportion of their licence (due to growing a relatively small irrigated
341 crop area in comparison to their licence volume) will be largely unaffected by the direct
342 impacts of climate change on irrigation need, unless their licenses are revised as part of the
343 abstraction reform plan.

344 In contrast, all surface water licences in all CAMS units are projected to have a higher
345 risks of being under mandatory 50% (Level 1) abstraction restrictions in the future period due
346 to reduced summer low river flows, but especially in northern and western England.

347 Although these regions are wetter than the south and east of the country, the river flows are
348 more sensitive to drought as groundwater contributes less baseflow to sustain river flows
349 during low rainfall periods due to the soil and geological characteristics of those regions

350 The results therefore show that the underlying drivers of increased future risk of
351 constraint on surface water abstraction for irrigation differ in space (due to spatial differences
352 in climate and hydrogeology) and between irrigators (due to differences in attitudes to risk
353 and availability of land that manifest in differences in headroom). However, it is

354 acknowledged that there are limitations to this study that arise due to the design of the
355 FutureFlows project (and associated datasets) and due to lack of data.

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

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

375 Finally, our derived relationships between the annual indicator of aridity (PSMDmax)
376 and surface water irrigation abstraction (expressed as annual licence headroom) assumes that
377 the cropped area, crop mix and irrigation technologies used within each headroom group in
378 each CAMS unit remain constant, due to the lack of spatial baseline data on irrigated

379 cropping distribution and the associated abstraction licences. Future land use change
380 projections are highly complex and subject to a high degree of uncertainty (Holman et al.,
381 2017). Previous landuse change modelling studies have demonstrated the importance of
382 future socioeconomic conditions and cross-sectoral interactions as drivers for change in the
383 agricultural sector, in combination with climatic conditions (Harrison et al., 2015). However,
384 these studies did not distinguish between irrigated and rainfed cropping or assess how the
385 distribution of crops such as vegetables and soft fruit will change in the UK in the future.
386 Regarding irrigation technologies, changes in irrigation efficiency in England are likely to be
387 relatively unimportant given the current high efficiency of irrigation due to the high capital
388 and operating costs that growers face. Similarly, as irrigation in the UK is supplemental to
389 rainfall and focused primarily on delivering high-quality produce, it is unlikely that growers
390 will switch to drought resistant varieties unless they can match food quality requirements.

391 Nevertheless, growers are likely to autonomously adapt to changing conditions.
392 Consequently, we have deliberately studied the future risk of having insufficient licensed
393 water separately from the risk of abstraction restrictions in a given year as their implications
394 and available management options at the farm level are very different. In the case of an
395 abstractor getting close to their abstraction licence limit, this has a relatively long lead time
396 and the farm business can adapt their activity to reduce the financial impacts. Such
397 adaptation can be anticipatory (long-term planning), such as investing in on-farm storage
398 and/or more efficient irrigation systems (Knox and Weatherhead 2005; Daccache et al.,
399 2015), seeking other alternative water sources (if available) or changing the crop mix and/or
400 the irrigated area. It can also be re-active (short-term adaptation), giving priority in that
401 season to high value crops or seeking to obtain additional resources through water trading
402 (Fereres and Soriano, 2007; Iglesias et al., 2009; Kahil et al., 2015; Rey et al., 2015). In
403 contrast, mandatory abstraction restrictions imposed by the regulator during a drought period

404 may have little forewarning and an unknown duration, providing limited coping strategies for
405 those farmers without an on-farm reservoir. The economic consequences of such restrictions
406 regarding crop yield and quality can be very severe (Rey et al., 2016). That is why irrigators
407 in some areas of eastern England agreed on early voluntary abstraction restrictions during the
408 last drought (2010-2012) to avoid mandatory ones later in the season (Rey et al., 2017).

409 As water availability risks increase in the future, abstraction management strategies
410 will need to evolve to meet competing needs in the face of expected increased climatic
411 variability whilst minimizing adverse economic impacts (Holman and Trawick, 2011).
412 Making the most of available water resources will become increasingly important through,
413 for example, providing flexibility to abstract water for on-farm reservoirs during summer
414 runoff events; re-allocating water held within unused or partly used abstraction licences in
415 dry years and enhancing water trading to release this potential, hence promoting both
416 economic and water use efficiency (Möller-Gulland, 2010; Rey, 2014); and strategic water
417 transfers from wetter to drier areas (Gupta and Van der Zaag, 2008; Water UK, 2016). These
418 may require a more collaborative approach to water management between abstractors and
419 environmental regulators and a greater role for Water Abstractor Groups (Leathes et al.,
420 2008; Whaley and Weatherhead, 2015a; Whaley and Weatherhead, 2015b). The outcomes of
421 this first national assessment of climate change impacts on supplemental irrigation water
422 availability risks highlights the importance of developing such collaborative approaches to
423 reduce future impacts whilst balancing competing demands and food security.

424 **5. Conclusion**

425 In Europe, climate change is expected to increase temperatures, modify rainfall
426 patterns, intensify drought frequency and severity, and lead to increased crop water demand.
427 Consequently, supplemental irrigation is likely to become more important to agriculture to

428 maintain crop yields and quality in currently humid climates, but abstraction is likely to face
429 increasing risk of being constrained during droughts to protect the environment and public
430 water supply. This study presents the first risk-based assessment of the future annual
431 probability of irrigators being unable to irrigate optimally due to the constraints of an
432 abstraction licensing system and/or mandatory abstraction restrictions during drought in
433 England. The results show that the causes of increased risk differ spatially, with future
434 constraints from volumetric abstraction licence limits becoming more important in the drier
435 parts of the country in the east England, and mandatory abstraction restrictions due to future
436 low river levels during droughts becoming more frequent in the north and west due to the
437 reduced buffering effect of baseflow from groundwater.

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

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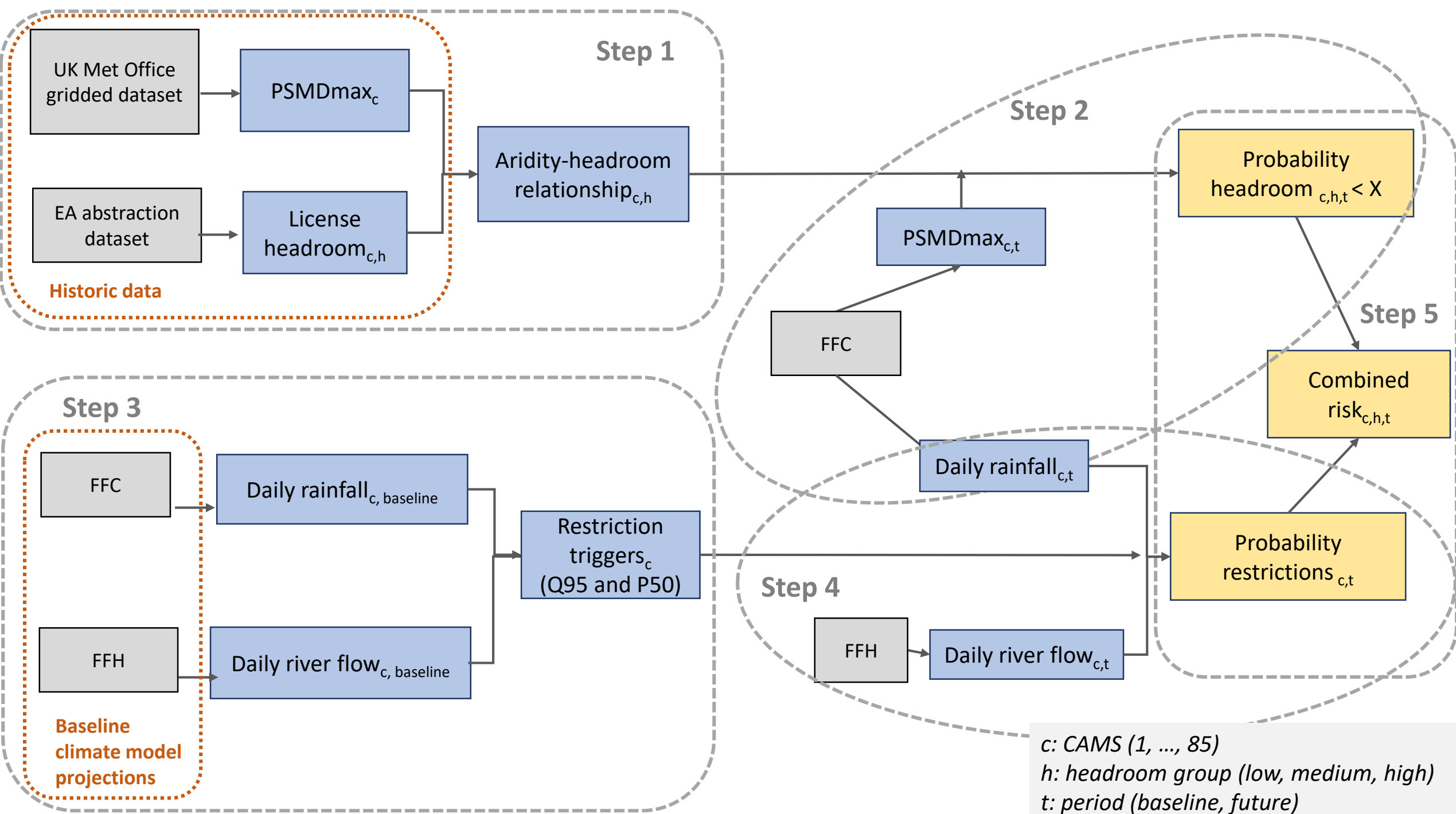
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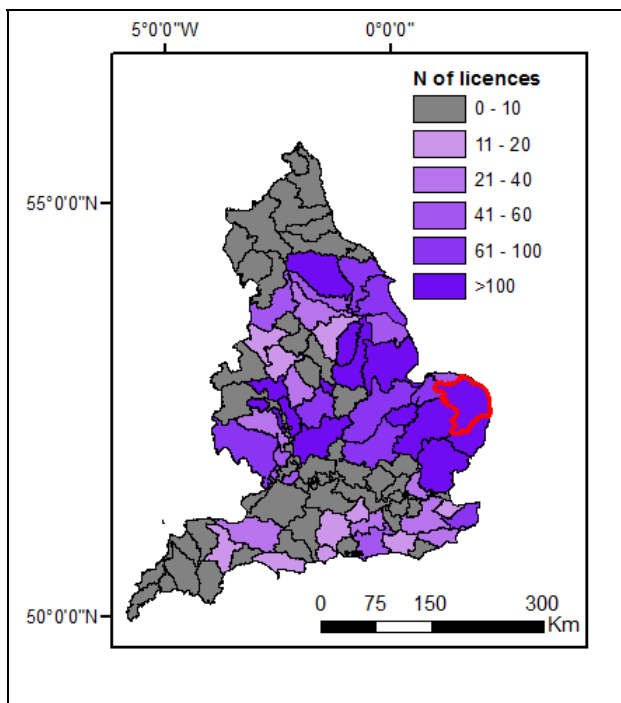
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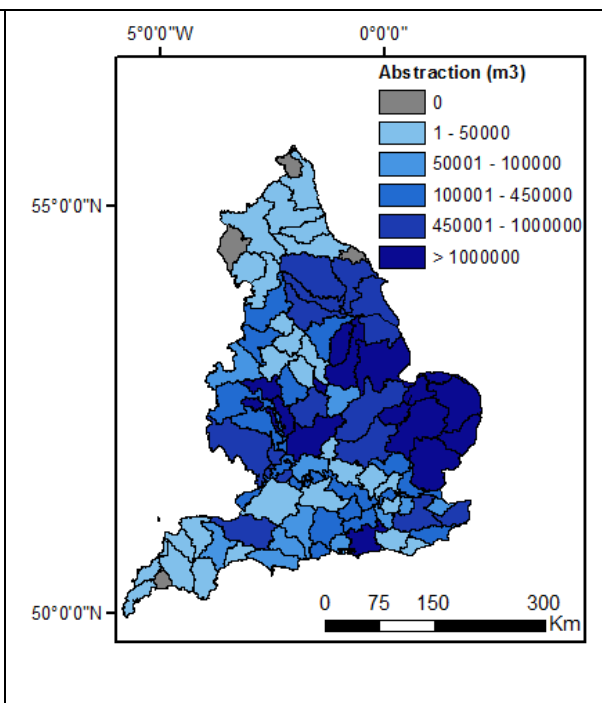
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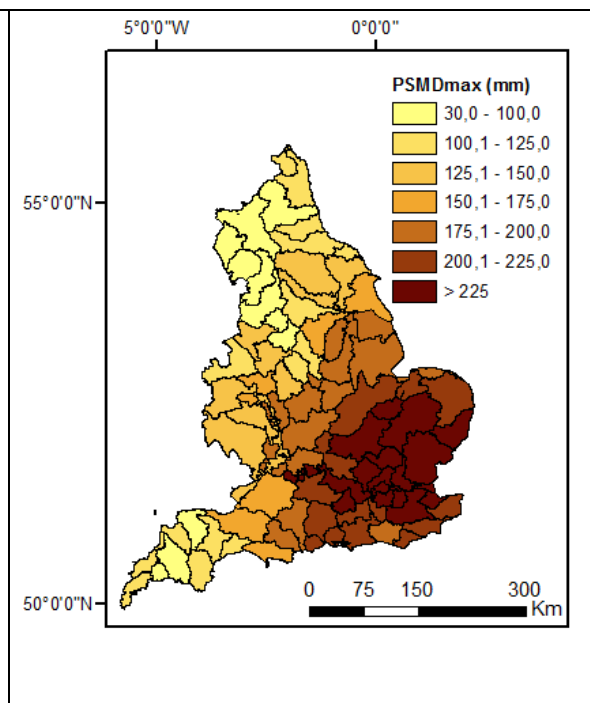
(a)



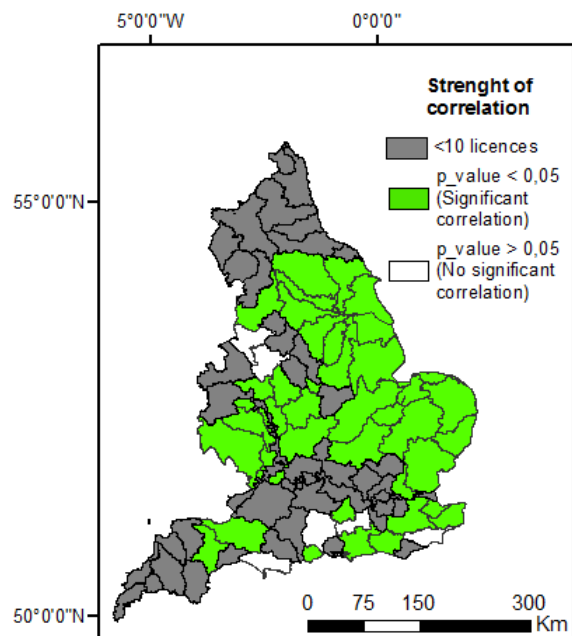
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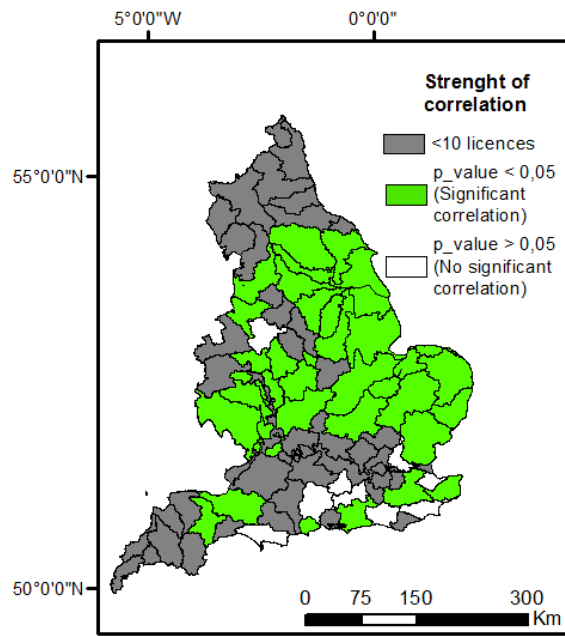
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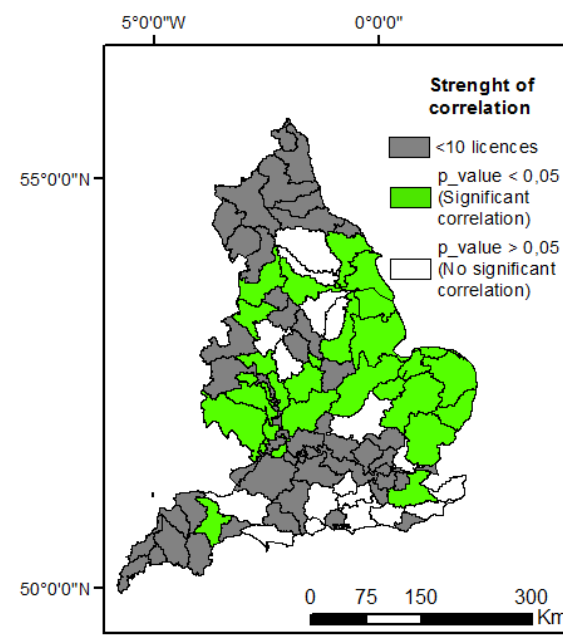
Low headroom

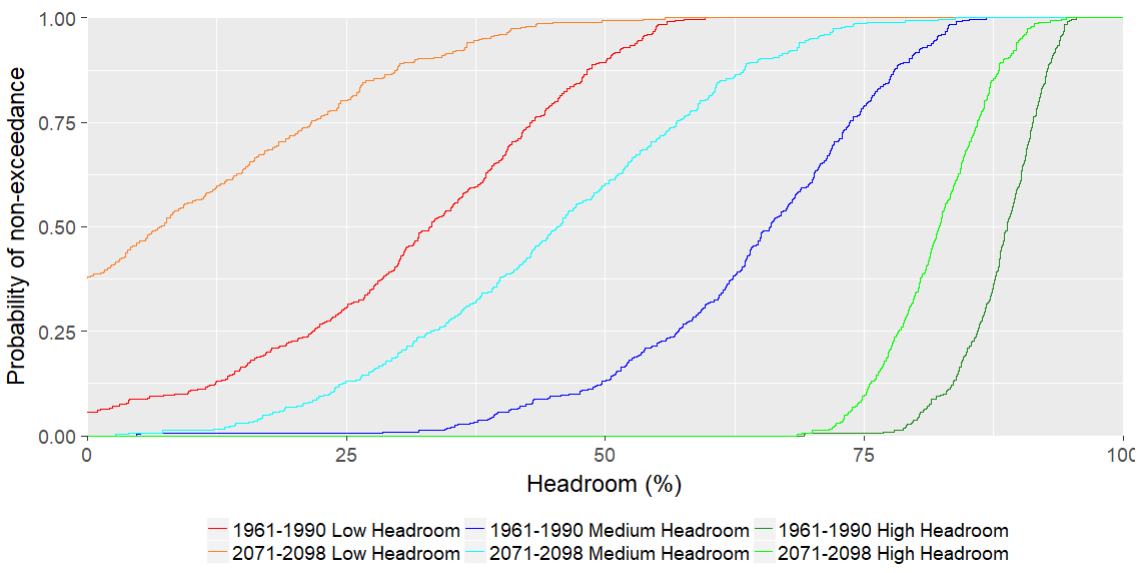
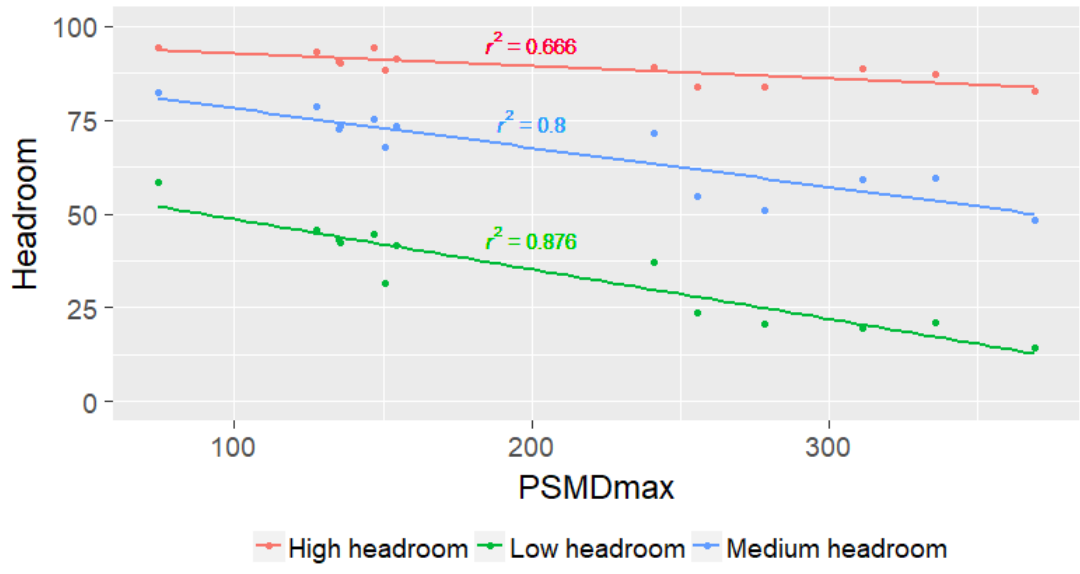


Medium headroom



High headroom





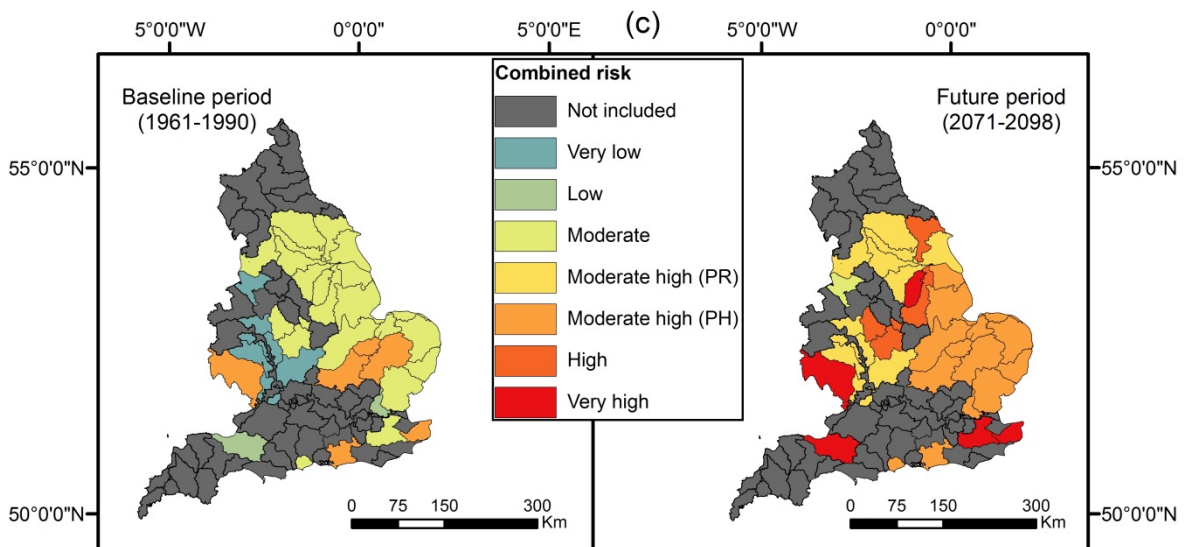
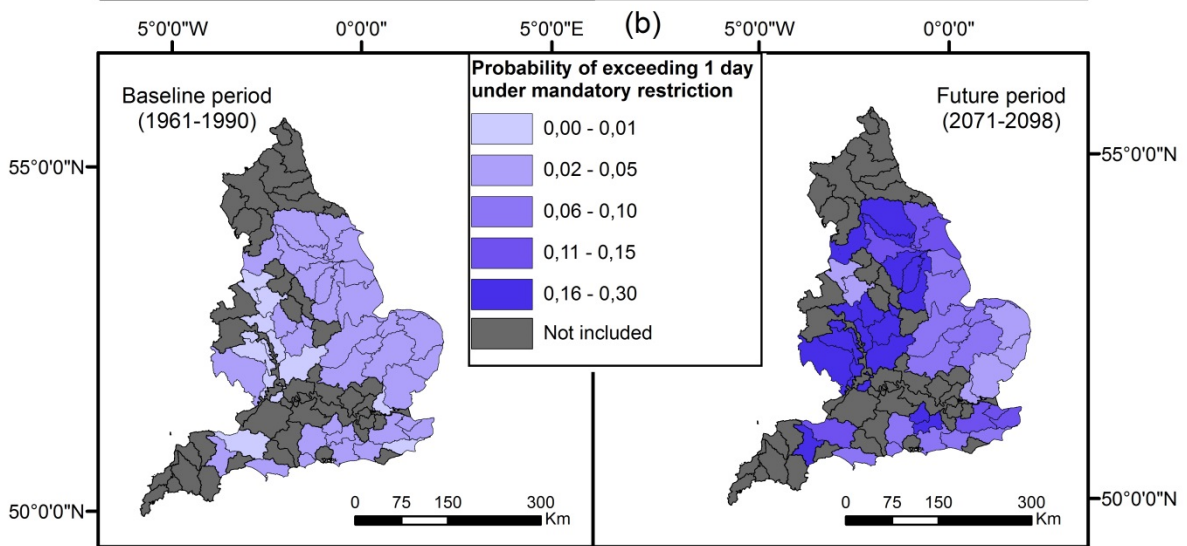
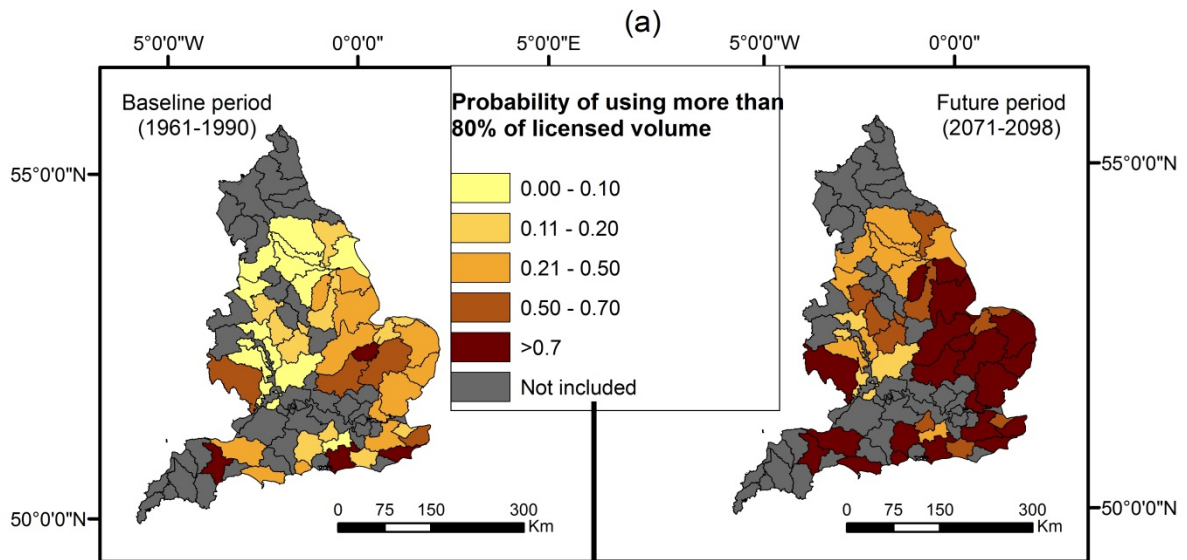


Figure captions

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 1999-2011; (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%