

1 **Scale impacts on spatial variability in reference evapotranspiration**

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5 **Abstract**

6 Evapotranspiration (ET) is one of the most important components in the hydrological cycle,
7 and a key variable in hydrological modelling and water resources management. However,
8 understanding the impacts of spatial variability in ET and the appropriate scale at which ET
9 data should be incorporated into hydrological models, particularly at the regional scale, is
10 often overlooked. This is in contrast to dealing with the spatial variability in rainfall data
11 where existing guidance is widely available. This paper assesses the impacts of scale on the
12 estimation of reference ET (ET_o) by comparing data from individual weather stations against
13 values derived from three national datasets, at varying resolutions. These include the UK
14 Climate Impacts Programme 50 km climatology (UKCP₅₀), the UK Meteorological Office 5
15 km climatology (UKMO₅) and the regional values published in the Agricultural Climate of
16 England and Wales (ACEW) (Smith, 1976). The national datasets were compared against the
17 individual weather station data and the UKMO₅ was shown to provide the best estimate of
18 ET_o at a given site. The potential impacts on catchment modelling were then considered by
19 mapping variance in ET_o to show how geographical location and catchment size can have a
20 major impact, with small lowland catchments having much higher variance than those with
21 much larger areas or in the uplands. Some important implications for catchment hydrological
22 modelling are highlighted.

23 *Keywords:* catchment; England and Wales; Penman-Monteith; regionalisation; water
24 resources.

25 **1 Introduction**

26 Evapotranspiration (ET) is the loss of water to the atmosphere via by the combined processes
27 of evaporation (from soil and plant surfaces) and transpiration (from plant tissues). It
28 constitutes an essential component in almost all hydrological water balance studies, whether
29 modelling the impacts of climate change on local river flooding (Booij, 2005), studying
30 changes in land use at a catchment scale (Holman et al., 2005) or predicting regional
31 agricultural irrigation demand (Rodriguez-Diaz et al., 2007). Although ET does not vary as
32 much as rainfall over short distances, taking into account its spatial variability can be
33 important, particularly if assessments are concerned with analysing extreme regional
34 phenomena such as droughts or desertification at the river basin scale (Dalezios et al., 2002).
35 Catchment ET is a function of the weather, land cover and wetness and measurement of actual
36 ET is difficult. Therefore, in many modelling studies, ET is estimated from a reference which
37 is a function of the weather and reflects the potential of the atmosphere to evaporate water.
38 This is modified for the particular surfaces under consideration by the use of an appropriate
39 crop coefficient (Pereira et al., 2015). Potential evaporation (PE: Penman, 1948), potential
40 transpiration (PT: MAFF, 1967) or potential evapotranspiration of a hypothetical surface
41 (ET_o, Allen et al., 1994a) have been used as the reference, among others (Pereira et al., 1999).
42 In many instances, the lack of spatially distributed ET data imposes a real limitation on
43 hydrological assessment, particularly when other datasets such as rainfall, land use and soils
44 are often available at high spatial resolutions. Even where meteorological data are available to
45 generate ET maps, their spatial accuracy will depend on the number of individual stations
46 used, their density across the study area and the interpolation methods employed (Foyster,
47 1973). Some water balance studies (e.g. Hess, et al., 2015) have applied ET estimation models
48 to small homogeneous units and then applied a weighted average to compute a regional based
49 ET estimate. Others have relied on remote sensing (satellite imagery) and surface

50 meteorological data to estimate ET, using for example, SEBAL (Surface Energy Balance
51 Algorithm for Land) (Bastiaanssen *et al.*, 2005).

52 The most common approach to addressing spatial variability in ETo seems to be selecting a
53 'representative' site with long-term historical meteorological data and then using this to
54 generate a dataset for input into a water balance model. The fundamental question is how
55 representative is the site to the larger study area, and what uncertainty does this geospatial
56 simplification introduce in hydrological modelling?

57 Despite the importance of reference ET in hydrological modelling there is surprisingly limited
58 research in the literature on assessing its spatial variability. For selected countries in Europe,
59 Gurnell (1981) produced isopleth maps of seasonal potential evapotranspiration (PET:
60 Penman, 1962) using a network of 70 weather stations and interpolating PET estimates using
61 polynomial trend surface analysis. Robbins-Church *et al* (1995) produced a series of regional-
62 scale ET maps for the northeast United States in support of water resource studies
63 investigating runoff and acidic deposition, and in Spain, Rey (1999) produced maps of ETo
64 based on the Penman-Monteith formula derived from a network of 920 thermopluviometric
65 stations for use in climate change impact studies on vegetation. Over the last decade, there has
66 also been major research progress in the application of remote sensing for deriving near real
67 time spatially distributed estimates of ET at regional and global scales (Mueller *et al.*, 2013).
68 For example, the MOD16 1 km² ET dataset covering the period 2000-2010 is now available at
69 8-day, monthly and annual intervals Mu *et al.* (2011). More recently, Cammalleri *et al* (2014)
70 developed a remote sensing data fusion methodology to map daily ET at the field-scale over
71 rainfed and irrigated agricultural areas using Landsat and MODIS data.

72 With competition for limited water resources and particularly given concerns regarding the
73 impacts of global changes in temperature and radiation (two important factors influencing
74 ETo), hydrological assessments need to recognise more explicitly the spatial variability in

75 ETo and its consequent impacts on water supply-demand balances. Over the last decade,
76 hydrological studies have benefitted significantly from the increased capability and
77 functionality of geographical information systems (GIS) enabling georeferenced databases to
78 be to integrated and spatially modelled. It is therefore surprising that many national and
79 international gridded climate datasets rarely include information on reference ET instead
80 preferring to leave estimation to the end user, recognising that there are many different
81 estimation methods.

82 **2 Approach**

83 Smith (1976) divided England and Wales into 52 agroclimatic regions, some of which were
84 further sub-divided, giving 71 discrete agroclimatic areas (Figure 1). The regions were based
85 on identifying areas with the greatest degree of uniformity in farming type, assuming that the
86 farming types within a particular region were a reflection of local climate and soil conditions.
87 This dataset is known as the Agricultural Climate of England and Wales (ACEW) and was
88 produced to provide growers, agricultural consultants, land resource planners and researchers
89 with a summary of important areal values for a range of key agrometeorological parameters
90 (Smith, 1976). The dataset contains a range of data based on direct measurements (e.g. mean
91 air temperature, rainfall and hours of sunshine), derived values (e.g. potential transpiration,
92 radiation) and agro-meteorological factors (e.g. length of growing season, soil moisture
93 deficit, date of return to field capacity). Although this climate atlas has been in circulation for
94 in excess of 40 years, many still rely on it as an alternate source of free (albeit non-digital)
95 data on the spatial variability of agroclimate for England and Wales. ACEW reported mean
96 monthly estimates for potential transpiration from a green crop (PT, Smith, 1976) which is
97 broadly analogous to ETo. PT was calculated for the period 1941-71 using the Penman
98 method (MAFF, 1967) for a large network of meteorological stations. PT isopleths were
99 drawn and the average monthly PT calculated for each agroclimatic region. The monthly

100 values quoted were “thought to be reliable within ± 2 mm” (Smith, 1976 p10) and were
101 designed for use at the “macro or possibly, meso-scale” (Smith, 1976 p12).

102 The UK Climate Impacts Programme (UKCIP) is responsible for providing a range of users
103 with climate data in support of climate change impact assessment. Since 1998, the UKCIP has
104 managed a climatology database containing both baseline (long-term average) and future
105 climate data (Hulme *et al.*, 2002; Jenkins *et al.*, 2009) for 50 km \times 50 km grid squares (Figure
106 1). The datasets contain long-term average (LTA) historical monthly data corresponding to
107 1961-1990 for a range of climate variables, including those required to calculate ETo.

108 The UKCIP climatology also includes a higher resolution (5 km \times 5 km) dataset based on
109 observed data produced by the UK Meteorological Office (UKMO) (Figure 1). This dataset
110 contains data for 36 monthly climate variables, for the period 1961-2011, of which 24 are
111 available free for research purposes via the UKCIP (Perry and Hollis, 2004) including those
112 required to calculate ETo.

113 Many methods have been developed to estimate PE or ETo relying on the integration of
114 meteorological parameters. The methods range from simple use of evaporation pan data
115 multiplied by a coefficient (Grismer *et al.*, 2002) to the use of empirical relationships (e.g.
116 Linacre, 1977) or more complex approximations of the physical processes involved based on
117 either temperature (e.g. Thornthwaite, 1948; Hargreaves and Samani 1982) or radiation (e.g.
118 Makkink, 1957; Priestley and Taylor, 1972; Turc, 1961). Substantial research effort has been
119 directed towards the development of combination methods, such as Penman (1948),
120 subsequently modified by Monteith (1965). A detailed review of ETo methods and their
121 accuracy is given in Allen *et al* (1994a). Following an extensive comparative assessment of
122 estimation methods, the FAO Penman-Monteith equation has been adopted as the standard in
123 both humid and arid environments by the International Commission on Irrigation and
124 Drainage (Allen *et al.*, 1994b); the Food and Agriculture Organisation of the United Nations

125 (Allen *et al.*, 1998); and the American Society of Civil Engineers (Allen *et al.*, 2005). ETo is
126 estimated from mean air temperature, net radiation, soil heat flux, mean wind speed and mean
127 vapour pressure deficit (Equation 1) (Allen *et al.*, 1998):

$$128 \quad \text{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [1]$$

129 Where,

130 ETo is reference evapotranspiration (mm d⁻¹); R_n is net radiation at the crop surface (MJ m⁻² d⁻¹);
131 G is soil heat flux density (MJ m⁻² d⁻¹); T is mean daily air temperature at 2 m height (°C);
132 u_2 is wind speed at 2 m height (m s⁻¹); e_s is saturation vapour pressure (kPa); e_a is actual
133 vapour pressure (kPa); Δ is the slope of the vapour pressure curve (kPa °C⁻¹), and; γ is the
134 psychrometric constant (kPa °C⁻¹). When not available, solar radiation can be estimated from
135 sunshine hours and soil heat flux can be estimated from change in daily mean air temperature
136 (Allen *et al.*, 1998).

137 The ACEW and UKCIP data sets allow estimates of potential or reference evapotranspiration
138 at a regional level (agroclimatic regions or grid squares respectively). However, these are
139 based on different data periods and regionalisations. This aims of this paper are therefore
140 threefold; (i) to compare PT and ETo estimated from ACEW and UKCIP respectively against
141 contemporary (1981 – 2010) estimates of ETo from individual weather station sites; (ii) to
142 compare ETo derived from the UKMO 5 × 5 km gridded data against contemporary (1981 –
143 2010) estimates of ETo from individual weather station sites to assess whether this could be
144 used to generate regionalised estimates of monthly average ETo; and (iii) to assess how
145 spatially-derived uncertainty in ETo estimates might then impact on catchment scale studies.
146 The analysis is undertaken for England and Wales but is relevant to other areas where
147 appropriate datasets are available.

148 The study comprised four sequential stages:

- 149 1. Three spatially distributed datasets of average monthly ETo were generated; one from
150 a published source and two based on gridded datasets of climate variables at $50 \times$
151 50 km and 5×5 km scales, respectively.
- 152 2. Each was compared with average monthly ETo from long-term historical (observed)
153 weather data from a network of weather stations to determine how well the spatially
154 averaged ETo data compared to estimates from individual weather stations.
- 155 3. The 5×5 km dataset was then used to map the spatial variability in ETo across
156 England and Wales.
- 157 4. Three regionalisations of ETo - based on agroclimatic areas, hydrological catchments
158 and an arbitrary grid - were compared in order to identify the most useful
159 regionalisation for summarising spatial variation in ETo.

160 As each stage depended on the outputs of the previous stage, the methods and results for each
161 stage are presented together. Finally, the relevance and importance of factoring in spatial
162 variation in ETo to hydrological modelling was considered.

163 **3 Spatially distributed datasets of average monthly ETo**

164 Data on temperature, solar radiation, wind speed and humidity were extracted from the 50 km
165 $\times 50$ km UKCIP data (Hulme *et al.*, 2002; Jenkins *et al.*, 2009) and mean monthly ETo for
166 each grid pixel was calculated using the method of Penman-Monteith (equation 1). These data
167 are referred to as UKCP₅₀ ETo.

168 The UKMO national 5×5 km gridded dataset was derived from a historical database
169 containing observations of weather elements from an irregularly spaced network of
170 meteorological stations across the UK (Perry and Hollis, 2004). The density of the station
171 network varied from an average of one station per $3,481$ km² for pressure, cloud and wind (70
172 stations), to 441 km² for maximum and minimum temperature (540 stations), to 49 km² for
173 rainfall (4400 stations) (Perry and Hollis, 2004). There was also considerable spatial

174 variation, with sparse data coverage in some regions, most notably in upland areas. However,
175 rigorous quality control procedures were applied to the daily observations by the UKMO,
176 including substitution of poor quality data, filling in missing data, and applying range and
177 consistency checks prior to creating the final gridded database. A detailed description of the
178 procedures used to produce a regular grid of values from the irregularly spaced station (point)
179 data and the climate interpolation (using inverse distance weighting and accounting for
180 altitude, terrain, distance from the coast and urbanisation) to generate the final gridded climate
181 dataset is given in Perry and Hollis (2004). Maximum and minimum air temperature, mean
182 relative humidity, sunshine duration and mean wind speed were extracted for each grid pixel
183 and monthly ETo was calculated for each year (1981 – 2010). The average of the 30 years
184 ETo for each month is referred to as UKMO₅ ETo.

185 **4 Performance of spatially distributed ETo**

186 *4.1.1 Individual weather stations (site)*

187 Fifteen weather stations were selected (Table 1) on the basis of having long-term
188 (corresponding to 1981 – 2010) average climate data available and reflecting the range of
189 agroclimatic conditions that exist across England and Wales. For each station and month,
190 long-term average ETo was calculated using the method described in Allen *et al.* (1998) from
191 long-term average maximum and minimum air temperature, sunshine duration and wind
192 speed given by the UK Met Office. Hourly records of dewpoint temperature or wet and dry
193 bulb temperatures were used to estimate long-term average (1981 – 2010) monthly vapour
194 pressure (Met Office, 2006). These estimates are referred to as ETo_{site} and range from
195 539 mm year⁻¹ at Durham to 676 mm year⁻¹ at Bedford (Table 2).

196 *4.1.2 Statistical comparison between individual site and national datasets*

197 The individual weather station (ETo_{site}) data were used as reference values against which each
198 national ETo dataset (ACEW, UKCP₅₀ and UKMO₅) was compared using two difference-

199 based statistical indicators; the root mean squared error (RMSE) and mean bias error (MBE)
200 (Jacovides and Kontoyiannis, 1995). The RMSE allows a comparison of the actual differences
201 between the $ET_{O_{site}}$ values and those estimated using the two gridded datasets (UKCP₅₀ and
202 UKMO₅) and the ACEW atlas. The smaller the RMSE value, the better the agreement
203 between the methods; however, the RMSE does not differentiate between under and over-
204 estimation of ET_{O} . The mean bias error (MBE) provides information on dataset accuracy,
205 with a positive value giving the average amount of over-estimation in ET_{O} and vice versa.
206 The smaller the absolute value, the better the agreement between the two datasets. For each
207 paired set of values, the RMSE and MBE were calculated for the winter (December to
208 February), spring (March to May), summer (June to August) and autumn (September to
209 November) periods, and then annually. As average $ET_{O_{site}}$ is considerably higher in summer
210 than winter, these were also expressed as a percentage of the long-term average $ET_{O_{site}}$ to
211 allow comparison of the performance of the alternative data set across seasons.

212 *4.1.3 Results*

213 A comparison between the mean monthly ET_{O} for each weather station ($ET_{O_{site}}$) and the three
214 national datasets (ACEW, UKCIP₅₀, and UKMO₅), by month, is given in Figure 2 to Figure 4.
215 The RMSE and MBE statistics (Table 3) show that ACEW underestimates $ET_{O_{site}}$,
216 particularly at low values of ET_{O} between August and March. This is partly due to the
217 different time periods used, but the use of PT as a reference in ACEW accounted for an
218 underestimate of 6% in annual ET (see Figure 5 which compares the two ET estimation
219 methods with the same climate data). The UKCP₅₀ and UKMO₅ values show a much closer
220 correlation with $ET_{O_{site}}$. Overall the UKMO₅ based estimates for ET_{O} fit more closely to the
221 $ET_{O_{site}}$ than either the UKCP₅₀ based estimates or the ACEW, with an MBE of zero, although
222 this results from an over-estimate in winter (MBE = 3.4 mm/month) and under-estimate in
223 summer (MBE = -3.6 mm/month).

224 **5 Spatial variation in ETo**

225 Given the temperate maritime climate and diverse topography of England and Wales, ETo can
226 vary quite substantially over relatively short distances; it is therefore important to account for
227 any spatial differences in ETo in hydrological modelling studies. Figure 6 shows the spatial
228 distribution of ETo based on the most accurate, and highest resolution of the three methods
229 considered above. Maps have been produced to highlight the spatial ETo differences for three
230 periods, (i) the month in which peak ETo rates generally occur (July), (ii) the summer period
231 (April to September) and (iii) annually.

232 For July, the highest ETo values (>100 mm) are recorded in eastern and south eastern
233 England, with pockets in London and along the south coast (where sunshine and radiation are
234 strongest). The lowland, inland regions show the greatest uniformity in ETo. The lowest ETo
235 values (<50 mm) are recorded in the upland regions notably in parts of Wales, the south west
236 and northern England. The summer and annual maps show a similar pattern but highlight
237 particular regions (e.g. West Midlands, parts of Lincolnshire, Kent) where seasonal ETo
238 values are much higher. The maps in Figure 6 should alert hydrologists and others modelling
239 at the catchment scale of the need to consider carefully the implications of spatial and
240 temporal ETo variability in their analyses.

241 **6 Regionalisation of ETo**

242 In practice, the choice of ETo data used for hydrological modelling is often governed by a
243 number of factors including the scale of enquiry, having access to high quality low cost
244 historical daily climate data, and the modellers' perception or knowledge of the extent to
245 which spatial variations in topography and land use might influence evapotranspiration rates.
246 The ETo maps (Figure 6) show how ETo varies spatially in England and Wales, however, one
247 important question that arises is the extent to which these spatial variabilities in ETo are
248 important at a range of scales.

249 Three regionalisations of England and Wales were compared (Table 4); the UKCP 50 km
250 boundaries; the ACEW agroclimatic regions (Smith, 1976); and the hydrological areas
251 defined by the Environment Agency (EA) as part of its catchment abstraction management
252 (CAMS) process (EA, 2010) (Figure 7). As the UKMO₅ dataset was shown to be the most
253 representative (based on the comparison with ETo_{site} above), it was used as the basis for
254 comparison. In order to compare the variation due to the regionalisation partitioning, two
255 methods were used: Variance component analysis and the Brown–Forsythe test (Brown and
256 Forsythe, 1974).

257 Variance component analysis was first used to compare the within-region variation under
258 each regionalisation. Using ANOVA, the variation of each regionalisation method comprises
259 two sources: (i) between regions variation is the variation due to difference between regions
260 means (denoted by $SS_{BR}^{(k)}$) and indicates the proportion of the total variation that is explained
261 by the differences among regions (Casella, 2008) and (ii) the remaining variation is due to the
262 within region variation which also shows the residual variation, or variation of each
263 observation around each region's mean. The within regions variation can be compared using a
264 pair-wise F-test based on the residual variance.

265 Table 5 summarises the variation analyses for the three regionalisation methods using the
266 variance component method. For January the UKCP 50 km regionalisation has the largest
267 contribution in the total variance (74%) which is significantly ($p < 0.001$) different to both the
268 EA CAMS and ACEW regionalisation methods which have the same contribution in the total
269 variance (54%). In July the UKCP 50 km regionalisation has the largest contribution in the
270 total variance (90%) and the CAMS regionalisation method has the lowest effect contribution
271 (86%). These suggest that the UKCP 50 km regionalisation is capturing the spatial variability
272 in ETo better than the other two methods.

273 The Brown–Forsythe method can be also used to assess differences in group variance among
274 the regionalisations. This method is more robust with respect to outliers and is ideal when the
275 distributions of data deviate even slightly from normality. In order to compare the
276 performance of the three regionalisations, the UKMO₅ data for January and July were
277 expressed as absolute deviations from the median for each region;

$$278 \quad d_{ij} = | ETo_{ijk} - E\tilde{T}o_{.jk} |$$

279 Where ETo_{ijk} is the UKMO₅ estimate of ETo for the i^{th} value in region j using regionalisation
280 method k , and $E\tilde{T}o_{.jk}$ is the median of the i values of ETo in region j for a given month. The
281 mean absolute deviation from the median (MAD) was calculated for each region in order to
282 compare the spatial variation of ETo among regions within a regionalisation, and an analysis
283 of variance of the transformed data used to compare the overall performance of the three
284 regionalisations.

285 Table 5 shows the MAD for the three regionalisations and two months. A pair-wise
286 comparison of the mean absolute deviation between the regionalisation methods confirmed
287 that the ACEW and CAMS regions are not significantly different from each other ($p=0.31$) in
288 January whereas in July, all three regionalisations are significantly different from each other,
289 reinforcing the conclusion of the variance component analysis. This suggests that the UKCP₅₀
290 grid provides less within-region variation in ETo than the other two regionalisations.

291 **7 Implications for hydrological modelling**

292 Figure 7 shows the MAD for each region within England and Wales according to the three
293 regionalisations.. Where MAD is low, the regional average ETo could be used with low
294 uncertainty, however, where it is high, spatial variability in ETo introduces larger uncertainty
295 and hydrological modelling needs to consider the spatial variability in ETo more explicitly.

296 In January, as the mean values of ETo are small, the MAD is also small, being <2 mm/month
297 for all regions and regionalisations with the exception of parts of north east England under the
298 ACEW and CAMS regionalisations. In the month of maximum ETo (July) the MAD is
299 generally low in eastern, central and southern England (all lowland areas) in all three
300 regionalisations, with the notable exception of the UPCP 50 km grid square around London.
301 The differing performance of the regionalisations is not simply a function of the size of the
302 regions. The CAMS regionalisation has the smallest mean region size of the three approaches
303 regionalisations, yet is least successful in capturing the within region variation. This may be
304 because, by definition, a hydrological catchment encompasses a range of topography from
305 headwaters to catchment outlet. Similarly, there is no overall correlation between CAMS size
306 and MAD. For example, although the Wye in south Wales is the largest (4,178 km²) and has
307 the third highest July MAD (5.4 mm/month), the Cam and Ely Ouse (3,664 km²) in eastern
308 England is the second largest CAMS area and has one of the lowest values of MAD in July
309 (0.9 mm/month).

310 The MAD values for ETo by CAMS areas are of particular relevance to hydrologists. This
311 map (Figure 7) identifies specific areas where both low and high MAD in July ETo occur, and
312 can be used in support of defining the ETo data requirements for hydrological studies. For
313 example, a number of small, lowland, inland CAMS areas have a low July MAD (< 1
314 mm/month). Studies in these CAMS areas could justifiably rely on using the catchment
315 average value of ETo. In contrast, a number of CAMS areas in northern England and Wales
316 all have high values of July MAD (> 4 mm/month). Many of these CAMS areas are in upland
317 areas and of varying size and studies should therefore carefully consider the spatial variability
318 in ETo within these areas in a more spatially explicit way. Readers interested in the
319 geographical distribution of CAMS catchments in England and Wales are referred to EA
320 (2010).

321 **8 Conclusions**

322 The comparison of the ACEW ETo regional estimates of PT and ET_{site} has shown that the
323 published regional values (Smith, 1976) are no longer fit for purpose. The use of PE is known
324 to underestimate ET due to insufficient consideration of the effect of wind speed (Thom and
325 Oliver, 1977) and this study has shown an underestimate of long-term average ET of 20%.
326 However, the 5 km resolution gridded data (Perry and Hollis, 2004) can be used to replicate
327 ETo at a point. The analysis of the regionalisations has shown that, perhaps surprisingly, the
328 agroclimatic regions of Smith (1976) are not the best way to summarise ETo in England and
329 Wales, rather an arbitrary 50 km grid provides less within-region variation and therefore
330 better accounts for the spatial variability of ETo.

331 There are hidden problems associated with either ignoring such variability or estimating ETo
332 using limited only climate data, which are of particular relevance to climate change impacts
333 research, and those concerned with assessments of hydrology on future water resources. For
334 these types of studies it is important to not only choose an appropriate method that provides
335 the most accurate estimate of ETo, within the constraints of data availability, but also avoids
336 introducing additional uncertainty into the subsequent hydrological modelling and analysis.
337 Failure to consider these issues at the outset may result in error propagation through the
338 methodology; with impact assessments reflecting errors in ETo estimation, rather than climate
339 change *per se*.

340 Using England and Wales as a case study, this paper quantifies and maps the impacts of scale
341 on ETo estimation by comparing data from a network of weather stations with long-term
342 historical data against equivalent values derived from three publically available datasets, all at
343 varying resolutions. These datasets have been widely used by scientists and others involved in
344 catchment-scale studies, most recently in climate impact assessments. However, in the
345 absence of alternative guidance, most have generally ignored the potential impacts that any

346 spatial ETo variability might have on their modelling approaches and simply assumed single
347 site data to be representative for large areal based water balance or climate impact
348 assessments. This study provides new valuable insight and information for the hydrological
349 research community to help understand the importance of spatial ETo variability and guide
350 the appropriate selection of ETo datasets for input into regional-scale modelling.

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356 <http://catalogue.ceda.ac.uk/uuid/916ac4bbc46f7685ae9a5e10451bae7c>. Long-term average 50
357 x 50 km data are available from <http://ukclimateprojections-ui.metoffice.gov.uk/>. The 5 x
358 5 km Gridded data sets are available from
359 <http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/>.
360 Derived reference evapotranspiration values are available on request from the authors at
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Appendix I: Definitions of evapotranspiration terms.

Term	Abbreviation used	Definition
Evapotranspiration	ET	The measured (or estimated / modelled) sum of evaporation and transpiration from a particular surface at the soil water content and agronomic condition at the time of measurement.
Potential evaporation	PE	Evaporation under conditions of full water availability and saturation at the surface so that vapour pressure deficit at the surface and surface resistance become null. It is analogous to Penman’s open water evaporation (Penman, 1948), thus it only applies to a crop after the crop surface has been wetted by rain or sprinkling.
Potential transpiration	PT	Potential evapotranspiration (Penman, 1962) or potential transpiration (MAFF, 1967) from an extensive surface of grass under stress-free conditions.
Potential evapotranspiration	PET	The two terms are broadly synonymous. However, as a “grass” surface may vary in terms of height, albedo and canopy resistance, PET and PT are potentially ambiguous terms.
Reference evapotranspiration	ET _o	The evapotranspiration rate from a (defined) extensive reference surface, not short of water. Several reference

		surfaces have been defined, but Allen et al. (1994) defined reference ET as ‘the rate of evapotranspiration from a hypothetical crop with an assumed height of 12 cm, a fixed canopy resistance of 70 s m^{-1} , and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground and not short of water’.
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Table 1 Meteorological summary for the weather stations used in this study.

Station	Lat°N	Long°E	Alt (m)	Agroclimatic area	Annual rainfall, 1981-2010 (mm)
Aberporth	52.139	-4.571	133	50	887.7
Bedford	52.134	-0.461	24	28	597.7
Blackpool	53.821	-3.054	12	9	882.7
Boscombe Down	51.161	-1.754	126	36	748.6
Boulmer	55.421	-1.600	23	1S	689.3
Durham	54.775	-1.583	70	5	651.1
Lyneham	51.503	-1.992	145	30	745.3
Manchester Airport	53.358	-2.267	74	14	867.1
Marham	52.651	0.569	21	24	652.6
Shawbury	52.794	-2.663	72	18N	659.9
St Mawgan	50.441	-5.003	95	40	1017.4
Valley	53.252	-4.537	10	47	841.1
Waddington	53.175	-0.521	68	17W	614.4
Wattisham	52.123	0.961	89	29	613.8
Yeovilton	51.006	-2.640	20	35	708.5

Table 2 Mean monthly ETo (mm month⁻¹) for each weather station.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Aberporth	21.0	23.9	38.8	58.2	81.1	87.1	91.6	80.9	58.6	39.4	23.7	20.3	624.5
Bedford	13.5	19.9	42.3	65.1	87.8	98.7	115.1	104.4	67.7	36.9	15.7	9.3	676.4
Blackpool	16.0	25.5	36.6	61.7	88.7	94.7	100.0	88.8	60.5	35.7	22.0	12.2	642.5
Boscombe Down	11.8	17.4	39.1	61.7	87.7	100.0	112.2	97.7	61.8	31.6	13.0	8.7	642.8
Boulmer	20.4	24.8	41.1	53.5	72.9	83.5	89.9	77.7	53.7	33.2	19.4	17.0	587.1
Durham	12.6	18.8	37.6	53.4	76.3	82.3	91.2	76.9	48.2	23.0	10.3	8.8	539.4
Lyneham	12.8	20.0	41.1	65.2	90.7	103.7	113.8	98.1	64.0	33.5	14.5	10.0	667.5
Manchester Airport	13.3	20.2	39.1	59.5	88.1	93.1	100.8	85.5	56.2	33.0	12.0	6.8	607.5
Marham	12.6	19.4	40.9	64.7	91.8	99.6	114.2	100.3	63.9	34.8	13.7	9.2	665.1
Shawbury	13.9	19.6	39.4	61.4	86.2	96.8	106.7	89.9	59.4	31.4	14.8	9.9	629.2
St Mawgan	17.9	23.3	40.3	62.6	83.8	91.9	97.8	86.6	61.6	40.1	23.8	16.1	646.0
Valley	22.4	24.5	39.7	59.5	85.9	91.4	96.3	83.9	61.1	41.7	26.5	19.6	652.7
Waddington	14.4	21.3	42.3	64.4	90.9	99.6	114.0	100.2	64.7	35.2	15.0	10.7	672.6
Wattisham	12.9	18.8	40.0	64.4	90.5	101.1	116.0	103.6	66.0	34.7	13.7	9.6	671.3
Yeovilton	14.2	19.8	41.2	63.1	88.7	100.7	109.8	95.2	62.3	33.9	15.3	10.5	654.9

Table 3 RSME and MBE (mm month⁻¹ and % of LTA ET_{O_{site}}) for comparisons between the weather station (ET_{O_{site}}) data and the three alternative datasets (UKMO₅, UKCP₅₀ and ACEW), by season.

Season [†]	ACEW		UKCP ₅₀ grid pixel		UKMO ₅ grid pixel	
	RMSE	MBE	RMSE	MBE	RMSE	MBE
Winter	11.8	-11.4	4.5	0.8	3.8	3.4
	73%	-71%	28%	5%	24%	21%
Spring	7.1	-6.6	10.8	-8.8	3.3	-1.8
	11%	-11%	17%	-14%	5%	-3%
Summer	14.4	-11.9	11.9	-8.1	4.4	-3.6
	15%	-12%	12%	-8%	5%	-4%
Autumn	13.4	-12.9	7.1	-1.3	3.3	1.8
	36%	-34%	19%	-3%	9%	5%
Year	12.0	-10.7	9.1	-4.3	3.7	0.0
	23%	-20%	17%	-8%	7%	0%

[†] Winter = Dec – Feb ; Spring = Mar – May ; Summer = Jun = Aug ; Autumn = Sep – Nov.

Table 4 Number and size of regions for the three regionalisations in England and Wales.

Regionalisation	Type	n	Size (km ²)	
			Mean	St Dev
UKCP 50 km	Grid	97*	1,542	920
ACEW	Climatological	68	2,223	1,191
CAMS	Hydrological	116	1,304	815

* Three coastal grid squares containing very small areas of land were excluded from the analysis.

Table 5 ETo variation comparison for three regionalisation methods for England and Wales in January and July.

Statistic	January			July		
	UKCP 50 km	CAMS	ACEW	UKCP 50 km	CAMS	ACEW
n	95	116	68	95	116	68
$SS_{BR}^{(k)}$	30267	22021	22144	460487	437739	451999
$SS_{Res}^{(k)}$	10535	19088	18965	48916	72500	58240
$d.f_{Res}^{(k)}$	6160	6144	6192	6160	6144	6192
FBR (p-value)	188.3 (10^{-6})	61.63 (10^{-6})	107.9 (10^{-6})	616.9 (10^{-6})	322.6 (10^{-6})	717.3 (10^{-6})
Between regions variation	74% ^a	54% ^b	54% ^b	90% ^c	86% ^d	87% ^e
Within regions variation	1.7	3.1	3.1	8.0	11.8	9.4
Mean Absolute Deviation (mm month ⁻¹)	1.0 ^a	1.1 ^b	1.2 ^b	2.0 ^c	2.4 ^d	2.2 ^e

^a Values with the same superscript are not significantly different.

Figure 1 Maps showing the (a) agroclimatic regions (ACEW) (b) UKCP₅₀ grid squares and (c) UKMO₅ grid squares for England and Wales. The markers show the weather stations used in the analysis.

Figure 2 Relationship between ETo_{site} and Agricultural Climate of England and Wales (ACEW) PT (mm month⁻¹), by month.

Figure 3 Relationship between ETo_{site} and UKCIP 50 km grid resolution dataset (UKCIP₅₀) (mm month⁻¹).

Figure 4 Relationship between ETo_{site} and UK Met Office 5 km grid resolution dataset (UKMO₅) (mm month⁻¹) by month.

Figure 5 Relationship between ETo_{site} and PT for 15 stations in England and Wales, by month.

Figure 6 Comparison of mean (1981 – 2010) monthly (July), seasonal (April - September) and annual ETo (mm), based on UKMO₅ data for England and Wales.

Figure 7 Mean Absolute Deviation (MAD) (mm month⁻¹) in ETo for three regionalisations in a) January and b) July.