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1 Embodied water imports to the UK under 2 climate change

3

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29

30 **Abstract**

31 Commodities such as food and manufactured goods, particularly those that rely on land and water,
32 are increasingly recognised as being potentially sensitive to climate change on a global scale,
33 suggesting that the international dimension is critical when considering future supply susceptibilities
34 of import-dependent countries such as the UK. In this paper, we estimate embodied water imported
35 to the UK for 25 economically significant and climate sensitive sub-sectors, then explore the current
36 and future susceptibilities of these sub-sectors under climate change. In 2010, these products
37 represented 31% of total UK imports by value (\$), and 12.8 billion m³ of embodied water. Of this rice,
38 bovine and pig meat production, plastics and paper account for about 60% of the volume of water
39 embodied in the import categories considered. By combining product-based water volume estimates
40 with economic and climate model information we show how the UK could be increasingly
41 susceptible to loss of these water supplements in the future. In doing so, we and provide an
42 indication as to how countries that depend upon climate-sensitive imported resources can account
43 for these dependencies in a systematic way. For example, international adaptation and development
44 funding may be targeted to the securing of supplies from existing exporting countries, or trade
45 relations may be encouraged with potential new suppliers who are likely to be less resource
46 constrained.

47

48

49 **1. Introduction**

50 A growing number of countries have undertaken formal climate change analyses focussing on risks
51 directly occurring in the country itself (e.g., Defra, 2012). However, fewer studies have appraised
52 risks to countries and their citizens that originate from the international dimensions of climate
53 change. It is now recognised that more detailed, and quantitative, analysis is needed to understand
54 the relative importance of both direct domestic risks and indirect international climate risks to the
55 UK – in particular those risks in the latter group that may affect the security of food supplies and
56 other essential commodities – and the implications for associated national policies.

57 This paper contributes evidence of international risks by examining the relationship between
58 projected water resource susceptibilities in the UK and its trade partners under climate change, and
59 the potential resulting effects on patterns of trade. Our chosen metric is the amount of water
60 embodied in the production of primary and manufactured goods that are subsequently exported to
61 the UK. The concept (also known as the ‘virtual water’ trade) was first introduced as a hydro-political
62 solution to potential regional conflicts over water scarcity (Allan, 1993). Contrary to public
63 perceptions of resource abundance, it is now known that in aggregate the UK is currently a net
64 importer of water (e.g., Canals et al., 2010; Chapagain and Hoekstra, 2008; Chapagain and Orr, 2008;
65 Yu et al., 2010).

66 In fact, it is estimated that approximately 70% of the total water used in production and
67 consumption in the UK (73 billion m³/year) is imported from other countries in the form of water
68 embodied in goods (Chapagain and Hoekstra, 2008). As such, the UK is one of the most water
69 import-dependent nations in the world, alongside a small number of other North European
70 countries and Middle Eastern states. This is a striking statistic, given that imports equate to just 15%
71 of the UK economy, by value (ONS, 2011). Water use per unit of production in the UK is higher than
72 many of the countries that currently export to the UK. Moreover, the UK is not able to substitute all
73 foreign imports for domestic production, so the role of international trade and implied access to
74 water is essential to maintaining current patterns of consumption.

75 Viewed another way, the total water volume needed to produce the goods and services
76 consumed by the UK population, including the water embodied in imports, is 51% of the total
77 national renewable water resource available (estimated to be 147 billion m³/year) (Chapagain and
78 Hoekstra, 2008). However, in parts of southeast England, actual and licensed water withdrawals
79 from the environment already exceed sustainable levels (EA, 2009). Furthermore, pressures on UK
80 water resources are projected to increase in the future, as a result of population growth (an
81 expected 12% increase over the next 20 years [ONS, 2010]), economic growth, and climate change
82 (ASC, 2012). Hence, the net flow in embodied water will also be an important, indirect determinant
83 of the future health of UK freshwater ecosystems.

84 Given the inherent complexity of water accounting, few studies have attempted to quantify
85 such water flows. Roson and Sartori (2010) use a computable general equilibrium (CGE) economic
86 model to identify the effects that embodied water trading in agricultural products has on GDP under
87 wet, middle and dry climate change scenarios of Mean Annual Runoff for 2050 in the Mediterranean
88 region. They find that trade as an adaptation option facilitates increases in national GDP and net
89 savings in embodied water. However, these gains are described as marginal; other public adaptation
90 measures are highlighted as being required to more fully manage climate change-induced water
91 resource constraints in the region. Konar et. al. (2013) also use CGE modelling to identify trade-
92 related water savings, at the global scale, for rice, oil seeds (soy) and wheat, and use three crop
93 productivity scenarios that account for precipitation, evapotranspiration and carbon dioxide (CO₂)
94 fertilisation in 2030. They also find that there are water savings to be realised through international
95 trade, and argue that these should be realised through reduction of existing trade barriers.

96 Whilst these studies identify potential trade effects at the regional and global scale the level
97 of aggregation does not allow for analysis of national-scale responses within relevant sectors and
98 sub-sectors. This paper therefore seeks to provide a more disaggregated analysis of potential climate
99 change risks to the trade in embodied water, with the intention of facilitating a discussion of the
100 alternative responses an importing country can introduce or promote by way of adaptation,

101 additional to trade expansion. In Section 2 we outline our method for the identification and
102 quantification of import sub-sectors that currently embody significant volumes of water, and for the
103 evaluation of their susceptibility to future climate change risks. In Section 3 we present our results
104 for 25 sub-sectors, and discuss these findings in Section 4. Section 5 then draws together our
105 conclusions.

106

107 **2. Data and Methods**

108 We characterise our method in the following series of steps. First, we identify 25 sub-sectors that
109 are both water-intensive and economically significant in terms of aggregate UK trade flows. Second,
110 for each commodity, we calculate average water consumption embodied in UK imports by country
111 of origin. Third, we categorise these exporting countries according to a measure of current water
112 scarcity. Fourthly, we match these patterns of water consumption to regionally disaggregated
113 climate change impacts projected for a time period centred on 2040. These steps enable the
114 classification of current (2010) and future (2040) sectoral susceptibility to water scarcity, and reveals
115 the least water secure donor regions. For illustrative purposes we show susceptibility of embodied
116 water flows to climate change under the SRES A1B emissions scenario, generated by the Met Office
117 Hadley Centre model HadCM3.

118

119 *2.1 Identification of significant sub-sectors*

120 A sample of trade sub-sectorsⁱ was identified on the basis of a mapping process that plotted the
121 economic significance of all sub-sectors (measured by import value) against the sensitivity to climate
122 of the production activities within the sub-sector. Further details of this mapping process are
123 provided in Watkiss and Hunt (2012). As a result of this mapping, UK import data (by value and
124 weight) for key countries of origin – i.e. those countries that currently provide at least 5% of UK

ⁱ Sub-sectors may comprise of a single commodity, or a number of commodities

125 imports of a given commodity (group)ⁱⁱ - was extracted from the UN Comtrade databaseⁱⁱⁱ for the
126 sample of 25 sub-sectors identified as being both climate-sensitive and economically significant.
127 Overall, our sample of commodities represents 31% of total import value to the UK in 2010. Amongst
128 the chosen sub-categories, the most important in terms of value to the UK economy were petroleum
129 (9%), pharmaceuticals (4%), manufactured chemicals (4%), organic chemicals (3%) and gas (2%).
130 Other economically important sub-sectors (such as construction, financial services, information
131 technologies, media and communication) are assumed to be climate insensitive and were not
132 included in the analysis. The method of sampling adopted necessarily means that many commodities
133 are excluded from the analysis, including product groups such as green beans, flowers and bottled
134 water, that have received attention in the wider “food miles” literature (Pretty et al., 2005).

135

136 *2.2 Quantification of embodied water in import sub-sectors*

137 Published water consumption unit (m^3/tonne) estimates for each commodity group were used to
138 calculate total water consumption for UK imports of those commodities by the key countries of
139 origin. Sources of data on unit water consumption estimates for different commodity groups are
140 given in **Table 1**, along with country-specific examples of per tonne water consumption associated
141 with these commodities. In general, country specific figures are available for water consumption per
142 tonne of product for crops and meat, but not for fish and industry, in which case regional generic
143 data were used. **Figure 1** (upper panel) presents unit (m^3/tonne) estimates for agricultural and
144 fishery products used to calculate the total water consumption embodied in UK imports of these
145 products. Lower bound estimates tend to be defined by imports from European countries whereas
146 higher estimates refer to imports with origins in other continents. In the case of bananas the highest
147 estimate is an anomaly (Hoekstra and Hung, 2002) and refers to water consumption for St Lucia of
148 over $12,000 \text{ m}^3/\text{tonne}$, compared with below $1000 \text{ m}^3/\text{tonne}$ from most other countries.

ⁱⁱ This metric is adopted in order to make the size of the analysis manageable and in order to ensure that focus on currently important exporting countries to the UK is retained.

ⁱⁱⁱ United Nations Commodity Trade Statistics Database: <http://comtrade.un.org/db/default.aspx>

149 **Figure 1** (lower panel) shows per tonne water consumption estimates for selected fuels,
150 minerals, chemicals and manufactured products that are then used to calculate the total water
151 consumption embodied in UK imports of these products. These single representative estimates for
152 each product are used for imports from all selected countries of origin. **Figure 1** shows a higher
153 estimate of 500 m³/tonne for plastics but calculations were also performed using a lower estimate of
154 8 m³/tonne. This large range reflects a variation in water use estimates for different forms of plastic
155 or industrial processes. For example, whilst Morawicki, (2012) presents values of 500 m³/tonne for
156 polyethylene, polystyrene and polyvinyl chloride, Katsoufis (2009) estimate 8.7 m³/tonne for
157 polyethylene and 8.27 m³/tonne for polypropylene.

158

159 *2.3 Categorisation of exporting countries by current level of water scarcity*

160 Current levels of water scarcity in countries exporting to the UK were classified using a widely
161 recognised indicator of water stress (Falkenmark et al., 1989). Countries were defined as not water
162 vulnerable (>2500 m³/person/year), vulnerable (1700-2500 m³/person/year), stressed (1000-1700
163 m³/person/year), or water scarce (<1000 m³/person/year).

164

165 *2.4 Matching sub-sectoral embodied water with climate change risks*

166 In order to assess future climate susceptibilities of activities in sub-sectors currently exporting to the
167 UK, data on current import value and water use for the selected sectors identified in the first step,
168 above, were combined with information on climate change. Specifically, future climate risks
169 identified as being potentially significant to water resource availability (**Table 2**) were first graded
170 using the matrix in **Table 3**, before being matched to the country-specific sub-sector data.

171 Climate risks were identified for one set of climate scenarios – reflecting data availability.
172 However, it is well known that climate model scenarios show very different geographical patterns of
173 change, particularly for precipitation, which is considered to be the most important driver of
174 freshwater resources. Total uncertainty in global precipitation (and temperature) projections is

175 conventionally divided into natural (internal) climate variability, climate model (structure and
176 parameter) uncertainty, and radiative forcing (scenario) uncertainty. Depending on region, natural
177 climate variability contributes 50-90% of total uncertainty over the next decade and remains the
178 dominant source of uncertainty for 30 years (Hawkins and Sutton, 2010). Following the Foresight
179 Futures project (Lewis et al., 2010), we refer to scenarios generated by an ensemble of Met Office
180 Hadley Centre model HadCM3 experiments under SRES A1B emissions scenarios to 2040. Climate
181 change scenarios were then matched geographically with the world regions from which UK imports
182 originate. World commodity regions were categorised into standard climate zones using the Giorgi
183 and Francisco (2000) regions.

184 Finally, potential climate risks were classified by expected severity and degree of uncertainty
185 of impacts by 2040 (**Table 3**). The two dimensional classification was based on expert judgement as
186 in the Foresight Futures project (Lewis et al., 2010). Uncertainty was classified on the basis of the
187 strength and consistency of the climate signal for specific climatic variables as indicated by the
188 output of a 17-member ensemble of HadCM3. The impact on individual commodities was classified
189 subjectively, based on a variety of (positive and negative) risks to production (**Table 2**). We capture
190 not only the direct effects on water resources as a result of changing precipitation patterns but also
191 some potential indirect impacts that might, for example, arise from temperature changes to crop
192 evapotranspiration. Tables 5 – 9 then present the combined data at a country level for five products
193 which are responsible for the most significant volumes of water use in UK imports in areas of
194 potentially increasing water scarcity. Thus, total water consumption used in producing the goods for
195 export to the UK is estimated, alongside the projected future climate risks on these goods in the
196 exporting countries.

197 The methods adopted in this study are based primarily on observed data. Consequently, this
198 means that results for future time periods must be inferred from present patterns of trade. For
199 maximum transparency, **Table 4** provides an evaluation of the individual methodological steps, with
200 attendant assumptions, and acknowledged limitations of our approach.

201

202

203 **3. Results**

204 *3.1 Current embodied water imports*

205 The full set of aggregate, country-based, statistics by commodity are shown in Supplementary **Tables**
206 **S1** to **S25**. Here we concentrate on the five most important water uses in volumetric terms, as well
207 as on the overall susceptibility across the 25 sub-sectors considered.

208 **Figure 2** shows total embodied water in all selected UK imports. It is evident that bovine
209 meat production, plastics and paper production contribute the largest quantities of embodied water
210 – in absolute terms – of the twenty-five import categories considered. Together, they account for
211 about 40% of the 12.8 billion m³ of embodied water in these twenty-five categories. Rice and other
212 meat categories (poultry, pig and sheep) account for a further one-third of the total.

213 These results confirm findings of previous studies showing the high relative significance of
214 the contribution of crops and livestock to the total water footprint of UK imports (Chapagain and
215 Hoekstra, 2008; Chapagain and Orr, 2008; Feng et al., 2011). In the case of the crop imports studied,
216 we estimate total virtual water flows to be about 4 billion m³/year whilst the comparable figure for
217 livestock is approximately 5 billion m³/year. These compare with an aggregate of 43-46 billion
218 m³/year for embodied water in all crops and livestock – domestically produced and imported – for
219 consumption in the UK (Chapagain and Hoekstra, 2008; Chapagain and Orr, 2008). To put these
220 quantities into perspective, the total amount of water abstracted in the UK for all agricultural uses
221 was 7.7 billion m³ in 2006, equivalent to one-fifth of the water utilised in the production of
222 agricultural products for export to the UK. Thus, it is clear that there is a substantial water deficit
223 resulting from the patterns of embedded water in agricultural products consumed in the UK.

224 Estimates for UK industrial product imports are much less developed than for crops and
225 livestock, reflecting their low importance in absolute terms in this regard. Based on crude
226 assumptions, earlier studies claim that the embodied water in these imports is in the range of 17.2
227 to 20 billion m³/year (based on statistics for 1997-2001) (Chapagain and Hoekstra, 2008; Chapagain
228 and Orr, 2008). By way of comparison, total embodied water in domestic production of industrial

229 products is less than 32 billion m³/year (Yu et al., 2010). Even though our study focused on a few
230 selected products, our estimates demonstrate that paper (1.7 billion m³/year) and plastics (1.5
231 billion m³/year) constitute a significant proportion of the total embodied volumes. We also
232 compared the relative importance of these sectors utilising both the economic and water metrics,
233 expressed in fractional terms. **Figure 3** shows that whilst the dominant economic sectors are energy
234 and manufacturing, with the exception of paper and plastics, the major water consuming sectors are
235 agricultural. This confirms the finding of previous research (Chapagain and Hoekstra, 2008).

236

237 *3.2 Future embodied water imports*

238 Country-level results are based on water scarcity data provided by the United Nations Environment
239 Programme (UNEP, 2008) (Supplementary **Tables S1 to S25**). This reveals current exporters with
240 water scarcity in North Africa and the Middle East, plus areas of water stress in East and South Asia
241 (notably China and India), Eastern and Southern Africa, and some European countries including
242 Poland and Denmark. In the future, a major additional factor in determining global water stress is
243 population size. United Nations (2004) projections suggest that the current upward trend in global
244 population will continue until at least 2030; the Medium projection is for a population of 8.9 billion
245 by 2050, compared to 7 billion in 2012, representing an increase of 28%.

246 Other regions are expected to become water-stressed in coming decades. One seminal study
247 suggested that under a variety of economic and demographic scenarios to 2025, 2055 and 2085,
248 even in the absence of climate change, populations in East and West Africa, Central Asia and Central
249 America could become increasingly water stressed (Arnell, 2004). When climate change scenarios
250 were taken into account water stresses was found to increase in other areas including the
251 Mediterranean, parts of Europe, Central and Southern America, and Southern Africa.

252 The five most important water uses, in volumetric terms, are rice, bovine meat, pig meat,
253 plastics and paper and paperboard (see summary results for these sub-sectors in **Tables 5 to 9**, and
254 full results in Supplementary **Tables S1 to S25**), though the high ranking of plastics reflects the use of

255 the upper end of the per tonne water consumption range; use of the lower end value results in
256 plastics being ranked 20th out of the 25 sub-sectors considered. Together, these commodities
257 constitute about 60% of the 12.8 billion m³ of the embodied water in our chosen imports. The total
258 value (\$) and water consumption (m³) of the given commodity imported to the UK from key
259 countries of origin was calculated along with total import value from all countries of origin for the
260 year 2010. Note that our results for 2040 are specific to the chosen climate scenario and, that where
261 no class is given in **Tables S1** to **S25**, information on the specific climate risk was not available.

262 India and Pakistan are the largest exporters of rice to the UK in monetary and water volume
263 terms, currently accounting for almost 40% of the total rice import value. However, **Table 5** shows
264 that next to Thailand, they are the least water-efficient rice producers exporting to the UK. This
265 inefficiency is likely to result from the substantial subsidies given to irrigation in these countries that
266 distort the true opportunity costs of rice production in South and South-East Asia (Rosegrant et. al.,
267 2002). Moreover, national-level statistics can conceal strong regional variations. For example, it is
268 known that despite current water stress, rice is grown extensively in the Punjab region to generate
269 export earnings that constitute an income that is higher than from alternative uses of the water
270 (Kumar and Jain, 2007) – a finding that serves to emphasise that water is only one of a number of
271 factor inputs that influence the viability of rice production. When we consider sensitivity to climate
272 change, it is clear that the majority of climate risks are judged to have potentially high impacts,
273 though the precipitation-driven risks have a high degree of uncertainty (category A3). In contrast,
274 temperature-related risks are expected to increase evapotranspiration affecting rice growth and
275 yields with greater likelihood (category C3).

276 **Figure 3** shows that bovine and pig imports are important components of UK embodied
277 water. Ireland currently accounts for over two-thirds of the total bovine meat import value to the UK
278 (**Table S8**). Other significant exporters are from Central and South America, Africa and Australia and
279 New Zealand. **Table 6** shows that water efficiency is found to differ between these world regions,
280 with European countries being twice- and three-times more efficient than Africa/Australia and

281 Central/South America, respectively. The severity of the future climate risks that these regions are
282 projected to face in relation to bovine meat production does not differ geographically. Across all
283 regions the effects of heat stress – which could increase demand for water cooling – is judged to be
284 both the most severe and most likely climate risk (Mader, 2003). **Table 7** demonstrates that the
285 same result is found for pig meat exports to the UK, where Denmark and Netherlands are the largest
286 exporters to the UK (**Table S10**).

287 The two most water-sensitive manufacturing commodity groups are respectively plastics and
288 paper (**Tables 8 and 9**, also **S22** and **S24**). European countries including Germany, Belgium and
289 Netherlands account for around one-half of the total import value of plastics to the UK. Since there
290 is no differentiation between water demand levels between countries – though S22 shows a
291 substantial potential range in the level of efficiency assumed, reflecting different types of plastic
292 products as well as alternative processes – these countries also account for the majority of water use
293 in volumetric terms. Potentially the most severe risk is from greater drought frequency and intensity
294 with indirect impacts on manufacturing processes and power generation if – for example – some
295 form of rationing of use was introduced. The same results are found for paper and paperboard –
296 where the two dominant exporters to UK are Germany and Sweden – which are also judged to be
297 vulnerable to drought risk (category B3).

298

299 **4. Discussion**

300 The five sub-sectors highlighted above provide several important insights. First, it is clear that they
301 reflect diverse but economically important commodity groups that are sensitive to a range of climate
302 change risks that vary in projected severity and likelihood. It is also clear from the scenario-based
303 analysis that the susceptibility of production of UK imports of these commodities to changing
304 patterns of precipitation is less certain than due to changes in temperature. However, it is also
305 evident that these two sets of climatic variables need to be viewed together since production is

306 potentially affected by inter-play of multiple climate – as well as non-climatic – pressures. Semenov
307 et al. (2012), for example, show that both annual means and extreme weather events associated
308 with precipitation and temperature are critical to wheat production. They also highlight the
309 influence of technologies on agricultural productivity judged likely to interact with climatic factors in
310 future time periods.

311 Both imported and domestic UK production could be simultaneously impacted by extreme
312 weather events. For example, bovine meat from Ireland equates to 71% of the import tonnage and
313 59% of the embodied water (from the selected countries). Given the geographic proximity of Ireland
314 to the UK, whenever the former is impacted by heat waves it is reasonable to expect that the latter
315 (and other nearby producers in northwest Europe) could be similarly affected. Therefore, the supply
316 reduction created by this type of weather, and consequent upward impact on consumer prices for
317 the commodity, could be even more serious than **Table 6** suggests. The same issue applies to UK and
318 Europe-wide pig meat (**Table 7**), paper (**Table 8**) and plastics (**Table 9**) production. Furthermore, it is
319 likely that these neighbouring states would be competing with the UK to secure the same
320 commodities from sources outside Europe.

321 The static approach adopted contrasts with previous macro-economic analyses of embodied
322 water in trade flows by making explicit the range of climate change effects to which the exporting
323 country sub-sectors will need to consider and perhaps respond in their activities. The analysis is
324 country-specific in both the fact that the value of these imports is important to the UK and that the
325 country of origin is identified. Therefore, the analysis is designed to highlight that current trade
326 partners of the UK may be impacted by climate change and that to retain this export market they
327 may need to place increasing emphasis on water management. Alternatively, in order to maintain
328 export earnings these countries may consider diversification in to less water-intensive industries.
329 Conversely, the UK may wish to protect the supply of certain commodities from specific countries, or
330 at certain cost levels, in which case the climate adaptation strategy would need to adopt an
331 international dimension that encourages water management measures in the countries exporting

332 these commodities to the UK. Alternatively, the UK could begin to consider developing new trade
333 relationships with countries that are likely to be less negatively impacted by climate change and who
334 would therefore provide either a lower-cost or more reliable supply of commodities.

335 Our analysis provides an indicative, broad-brush, impression of UK import susceptibilities to
336 international climate change risks. Several future research priorities emerge from this high-level
337 scoping of the susceptibility of UK import production to climate change induced water scarcity. First,
338 a greater range of country- or region-specific climate change scenarios could be explored for the
339 most climate sensitive import sectors. Second, more detailed commodity-focussed case studies
340 could be undertaken that utilise quantitative climate change analysis to estimate the potential scale
341 of these future risks relative to current water sensitivities. Third, indices of embodied water could be
342 developed that incorporate measurement of sub-national water scarcity, both for current and future
343 climate scenarios. These indices would benefit from making the distinction between the different
344 sources of water used in production, i.e. directly rain-fed – known as “green water” - and water from
345 water courses and aquifers – known as “blue water”, and incorporating a measure of the
346 differential opportunity costs associated with these sources. This research would therefore down-
347 scale existing global-level analyses reported in, for example, Rost et al. (2008) and Konar et al.
348 (2012).

349 In due course, UK international development/adaptation strategies might target areas from
350 which UK imports currently originate or encourage alternative trade partnerships in less climate-
351 sensitive regions, thereby reducing the susceptibility of supply. Thus, a fourth research priority is to
352 explore alternative adaptation options/strategies in a number of case study contexts where climate
353 change is projected to significantly alter water resource availability in domestic production, and
354 where a sub-national region or country has a particular exposure to water-embodied exports.

355 In support of these research priorities, it would also be useful to explore the extent to which
356 the aggregate form of CGE macro-economic modelling undertaken by Konar et. al. (2013) could be
357 tailored, thereby allowing a move away from a static analysis to a more dynamic form of analysis.

358 For instance, such modelling could be used to identify for what commodity-climate scenario
359 combinations it is advantageous – given current and plausible future trade partnerships – for a major
360 importing country such as the UK to invest in supporting existing export partners and/or to
361 encourage diversification of trade partners. Such dynamic modelling approaches will be rendered a
362 great deal more realistic if – as identified in **Table 4** - the constraints imposed by our use of current,
363 observed, data are relaxed by the use of scenario-generated data sets relevant to each of the main
364 methodological steps adopted in the analysis.

365

366 **5. Conclusions**

367 The UK is susceptible to pressures on global water resources because the national water footprint
368 and water import dependency are relatively high even before climate change and population growth
369 are considered. Without aggressive water-saving and efficiency measures or compromised
370 environmental quality, there is limited scope for substitution of imported goods by domestic
371 production unless there are price increases, though, of course, the market economy allows for
372 substitution of goods and trade partners, with their own associated economic welfare losses.
373 Likewise, some of the UK's most important water-trading partners (notably Denmark, Ireland and
374 Germany in Europe - responsible for exporting the highest quantities of embedded water in pig
375 meat, bovine meat and plastics to the UK, respectively - and India and Pakistan in South Asia, who
376 are responsible for the highest quantities of embedded water in rice exports to the UK) are similarly
377 water scarce and facing increasing scarcity from climate change in the future. Climate change-
378 induced changes in international comparative advantage are therefore likely to lead to evolving
379 trade patterns and relations. Hence, climate risks to the UK water balance – and those countries
380 with similar susceptibilities - will need to be managed alongside other, better understood, drivers of
381 demand including terms of trade, demographics, consumer behaviour and dietary trends, policies
382 surrounding national food security, environmental standards, and competing land uses.

383

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386

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492 **Table 1** Sub-sector commodities with country-specific example data of per tonne embodied water in
 493 commodity production exported to the UK, and including principal data sources

Commodities	Examples	Data sources
Crops	Tomatoes [Spain], 76 m ³ /tonne	Foresight Futures (2011); Watkiss and Hunt (2012)
Meat	Bovine [Ireland], 6513 m ³ /tonne	Mekonnen and Hoekstra (2011)
Fish	Prepared/preserved fish [Thailand], 15 m ³ /tonne	Hoekstra (2003)
Petroleum	Oil refining [Norway], 2 m ³ /tonne	Seneviratne (2007)
Gas	Natural gas processing and transport [Qatar], 0.11 m ³ /GJ	Gerbens-Leenes et al. (2008)
Coal	Coal mining [Russia], 5 m ³ /tonne	Chi (2008)
Metal ores and scrap	Iron ore [India], 0.27 m ³ /tonne	Tata Steel (2012)
Pharmaceuticals	Average of five Analgesics [Germany], 128 m ³ /tonne	Verma (2011)
Chemicals	Organic chemicals [Netherlands], 40 m ³ /tonne	Environwise (2003)
Iron and steel	Steel manufacturing [France], 3 m ³ /tonne	International Mining (2007)
Plastics	Polythene, polystyrene, polyvinyl [Belgium], 8 to 500 m ³ /tonne	Katsoufis (2009); Morawicki (2012)
Paper	Paper and paperboard [Germany], 300 m ³ /tonne	Morawicki (2012)
Electric current	Nuclear generated electricity [France], 0.09 m ³ /GJ	Gerbens-Leenes et al. (2008)

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496 **Table 2** Examples of climate risks affecting production in countries exporting to the UK. Adapted
 497 from Lewis et al. (2010).

Sector	Climate risks (effect)
Agriculture	CO2 fertilization (crop yield); sea level rise (arable area); salt water intrusion (crop yield); storm and flood (damages crops); droughts and changing seasonality of snow/ice melt (water security); hot spells (crop yield and quality); higher minimum temperatures (crop yield)
Livestock	Sea level rise and salt water intrusion (pasture area); storm and flood (impaired feeding); drought (pasture); less frequent freezing (hypothermia and dehydration of stock); higher winter temperatures (pests and disease); hot spells (heat stress)
Manufacturing	Sea level rise and salt water intrusion (fresh water supply); storm and flood (damage to infrastructure); changing seasonality of snow/ice melt and drought (water security); surface runoff (water storage and reliability); drought (water security and power generation); higher temperatures (water demand and conflict)
Petroleum and gas	Sea level rise and surge (rig stability and disruption); storm and flood (disruption and infrastructure damage); drought (efficiency of extraction); higher temperatures (ice on rigs); drought (subsidence)

498

499 **Table 3a** Classes of climate change impact severity and uncertainties (upper box) adapted from
 500 Lewis et al. (2010).

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		Magnitude of Impact			
		Minimal Impact (0)	Low Impact (1)	Medium Impact (2)	High Impact (3)
Degree of Uncertainty	Changes Unknown (A)	A0	A1	A2	A3
	Some signal (B)	B0	B1	B2	B3
	Strong Signal (C)	C0	C1	C2	C3

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 505

506 **Table 3b.** Classes of water availability (lower box) based on current (2010) water scarcity categories
 507 used by the United Nations Environment Programme^{iv}.

Not vulnerable (>2500 m ³ /person/year)
Vulnerable (1700-2500 m ³ /person/year)
Stressed (1000-1700 m ³ /person/year)
Water scarce (<1000 m ³ /person/year)

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^{iv} <http://www.unep.org/dewa/vitalwater/jpg/0221-waterstress-EN.jpg>

511 **Table 4** Evaluation of study methods

Methodological step	Assumptions	Limitations
Identification of significant sub-sectors	Selected sub-sectors are representative of those imports to the UK that are most sensitive to water-related climate change risks. The countries focused upon according to current shares of UK import trade are assumed to be those who will continue to export to the UK.	The selection of the sub-sectors is based on a) those currently economically important (on the basis of import value); b) those that are currently climate-sensitive. The sub-sectors chosen by both criteria may change in future time-periods as economic and technological development proceeds.
Quantification of embodied water in sub-sectors	Data on current sub-sectoral per tonne water consumption is representative of water use intensities in future time-periods	Sub-sectoral water use intensities represent current patterns. However, these may change in the future in the face of technological change. Indeed, the countries of import origin may change with developments in future trade, thereby changing the relevant water use intensities.
Categorising exporting countries by current water scarcity	The indicators of water scarcity chosen – m ³ /person/year – are assumed to reflect the relative water scarcity faced by the selected sub-sectors in the relevant countries.	The water scarcity indicators are country-specific. They would therefore not capture sub-national differences in water scarcity resulting from geographical variations this scale.
Matching sub-sectoral embodied water with climate change risks	Future projections of climate change risks adopted in the analysis are plausible	The set of climate change risks identified for use in this analysis are taken from one climate scenario and therefore do not reflect the full range of uncertainties attendant to current projections. The results are therefore illustrative of potential susceptibilities.

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514 **Table 5** Climate Change Risks and Embodied Water in UK Imports: Rice

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Country	Total water consumption on UK imports (m3)	Higher min temps harms yield	Crop vulnerability to hot spells	Risk of drought results in reduced yield	Flood risk to crops	Reduced water availability from changing melt patterns	Storm risk to crops	Salt water intrusion risk to crops	CO2 fertilisation
Europe & Med									
Spain	118,020,465	C3	C3	A3	A3		A3	B2	C2
Italy	71,697,270								
NL	32,090,990			B3					
Belgium	16,666,664								
North America									
USA	76,205,074	C3	C3	A3	A3		A3	B2	C2
East Asia									
China	115,776	C3	C3	A3	A3	A3	A3	B2	C2
Southeast Asia									
Thailand	246,268,044	C3	C3	A3	A3		A3	B2	C2
Vietnam	207,648			A3	A3		A3		
Central & S. America									
Uruguay	18,097,317	C3	C3	A3	A3	A3	A3	B2	C2
Argentina	286,300			B2					
South Asia									
India	413,634,550	C3	C3	A3	A3	A3	A3	B2	C2
Pakistan	325,057,831								

517

518 **Table 6** Climate Change Risks and Embodied Water in UK Imports: Bovine Meat

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Country	Total water consumption (m3)	Heat stress negatively impacts on animal health/productivity	Warmer winters may result in disease & pests surviving	Reduced frozen water reduces hypothermia and dehydration risks	Lower summer rain may reduce pasture growth for cattle	Risk of flooding/feeding difficulties	Salt water intrusion risk to grazing pastures
Europe & Med							
Ireland	1,094,672,475	C3	B2	C2	B2	A2	B2
Netherlands	97,714,539						
Germany	48,769,344						
Italy	20,235,891						
Belgium	17,904,237						
Poland	12,140,232						
France	18,060,549						
Spain	15,520,479						
Denmark	6,929,832						
Central & S. America							
Uruguay	175,353,024	C3	B2	C2	C2	A2	B2
Brazil	37,475,424						
Africa							
Namibia	114,918,825						
Botswana	97,977,740						
Australia & NZ							
Australia	64,629,774	C3	B2	C2	B2	A2	B2
New Zealand	42,281,870						

521

522 **Table 7** Climate Change Risks and Embodied Water in UK Imports: Pig Meat

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524

Country	Total water consumption (m3)	Heat stress negatively impacts on animal health/productivity	Warmer winters may result in disease & pests surviving	Reduced frozen water reduces hypothermia and dehydration risks	Lower summer rain may reduce pasture growth for cattle	Risk of flooding/feeding difficulties	Salt water intrusion risk to grazing pastures
Europe & Med							
Denmark	441,832,611	C3	B2	C2	B2	A2	B2
Ireland	206,776,723						
NL	285,621,781						
Germany	214,301,594						
Belgium	215,320,264						
France	133,202,175						
Spain	72,081,975						

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526 **Table 8** Climate Change Risks and Embodied Water in UK Imports: Paper

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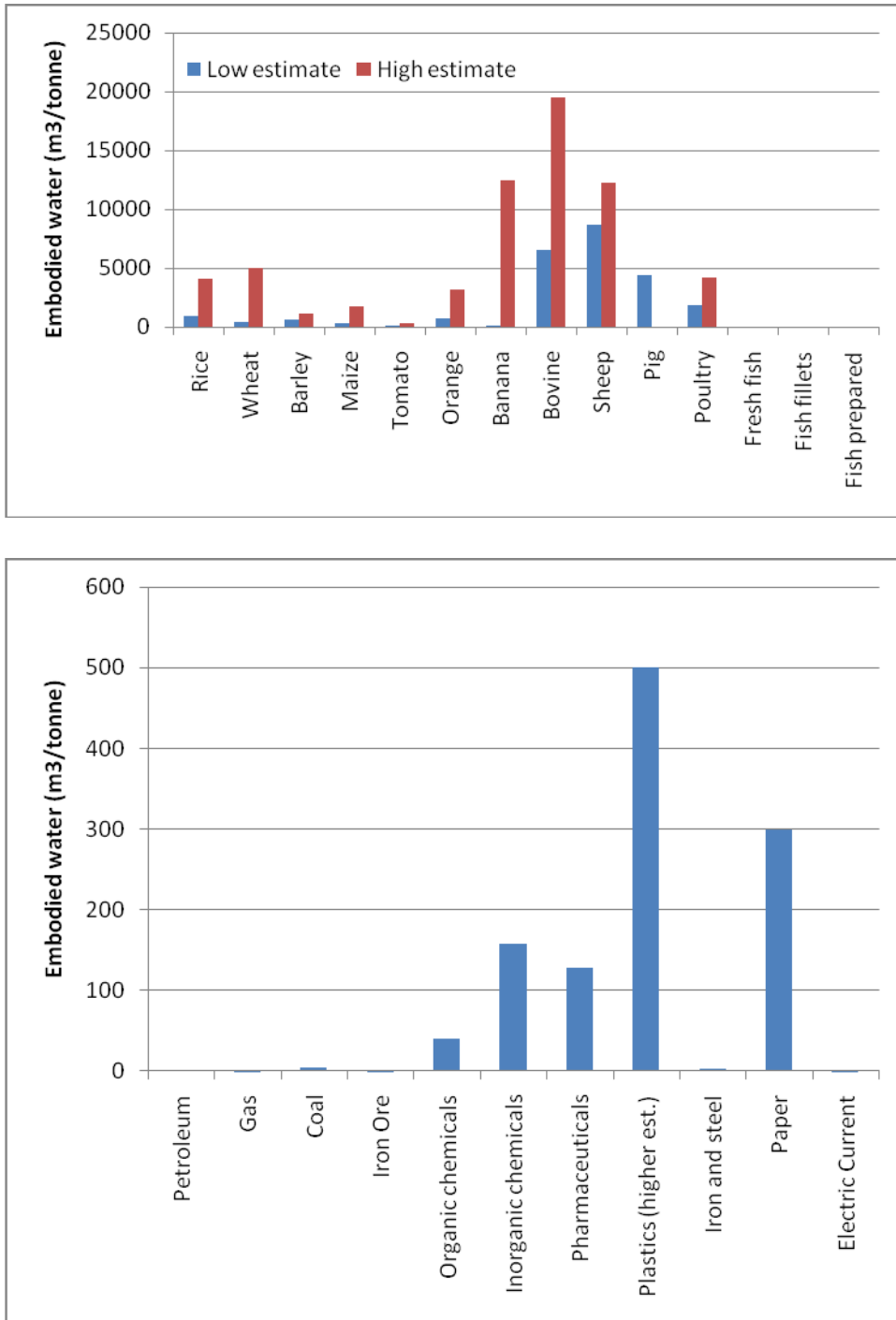
Country	Total water consumption (m3)	High temps - greater demand for water & conflict	Drought limits production & power generation	Greater surface run-off enhances water availability	Changes in precipn may result in water stress	Risk to water storage & availability	Salt-water intrusion to coastal aquifers
Europe & Med							
Germany	5,649,472	B1	B3	B1	A2	A2	C1
France	3,159,000						
Spain	612,120						
Italy	905,072						
Switzerland	37,176						
Netherlands	5,135,248						
Belgium	6,440,952						
Ireland	446,712						
Sweden	344,856						
Czech Republic	141,048						
Poland	189,504						
Austria	200,728						
North America							
Canada	4,864	B1	B3	B1	A2	A2	C1
USA	732,808						
East Asia							
China	112,200	B1	B3	B1	A2	A2	C1
Japan	106,440						
S. Korea	176,136						
Southeast Asia							
Malaysia	19,040	B1	B3	B1	A2	A2	C1
Thailand	116,336						
Central & S. America							
Mexico	67,752	B1	B3	B1	A2	A2	C1
South Asia							
India	20,208	B1	B3	B1	A2	A2	C1

530 **Table 9** Climate Change Risks and Embodied Water in UK Imports: Plastics

531

Country	Total water consumption (m3)	High temps - greater demand for water & conflict	Drought limits production & power generation	Greater surface run-off enhances water availability	Changes in precipn may result in water stress	Risk to water storage & availability	Salt-water intrusion to coastal aquifers
Europe & Med							
Germany	470,640,400	B1	B3	B1	A2	A2	C1
France	209,198,010						
Spain	60,977,476						
Italy	86,999,621						
Switzerland	1,523,969						
Netherlands	119,687,103						
Belgium	58,858,964						
Ireland	14,947,406						
Sweden	412,755,138						
Czech Republic	14,663,357						
Poland	35,459,434						
Austria	61,475,193						
North America							
Canada	53,294,270	B1	B3	B1	A2	A2	C1
USA	70,358,403						
East Asia							
China	69,189,183	B1	B3	B1	A2	A2	C1
Japan	1,524,204						
S. Korea	2,600,687						
Southeast Asia							
Malaysia	1,894,769	B1	B3	B1	A2	A2	C1
Thailand	320,327						
Central & S. America							
Mexico	276,803	B1	B3	B1	A2	A2	C1
South Asia							
India	7,458,270	B1	B3	B1	A2	A2	C1

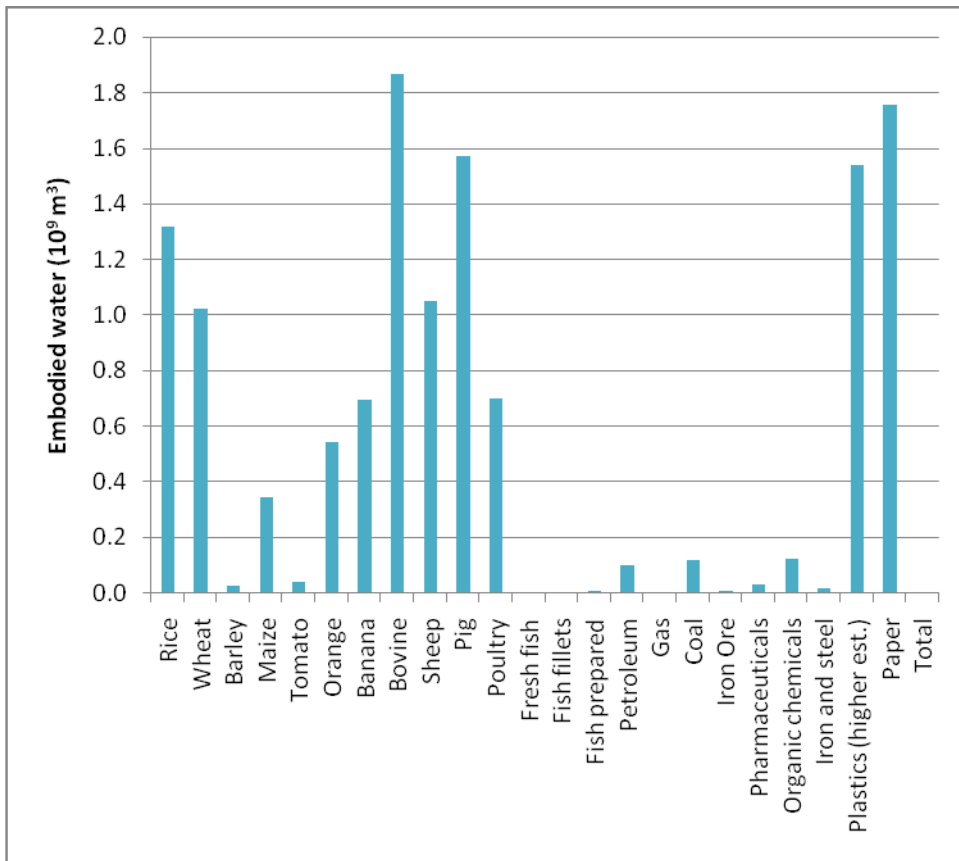
534 **Figure 1** Per tonne embodied water estimates for selected agricultural and fishery products (upper
 535 panel), fuels, minerals, chemicals and manufactured products (lower panel)



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538 **Figure 2** Total water volumes embodied in selected UK imports (2010)

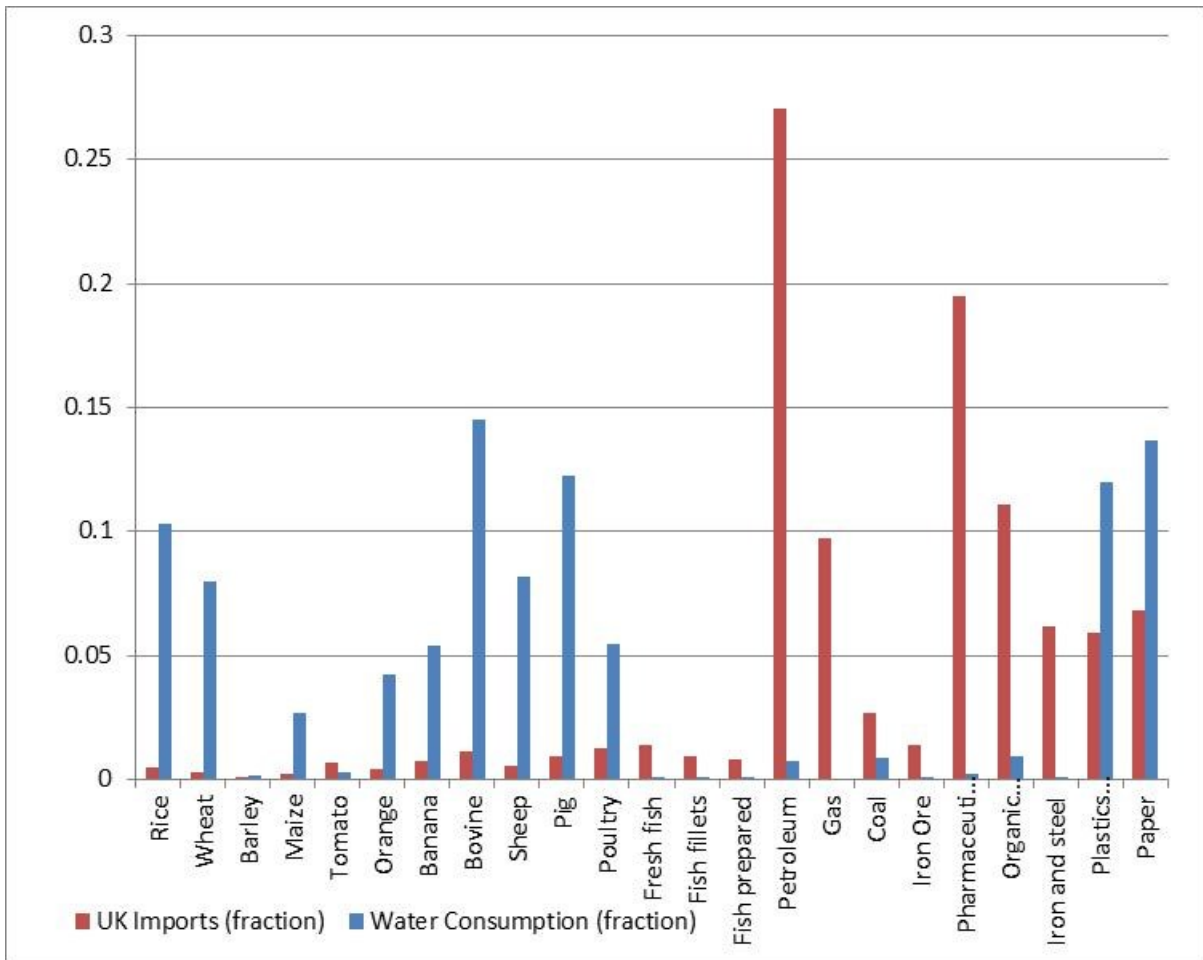


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542 **Figure 3** Fractional economic value and water consumption for selected UK imports in 2010



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