Embodied water imports to the UK under climate change

Alistair S.P. Hunt[1], Robert L. Wilby[2], Nick Dale[1], Kiran Sura[3] and Paul Watkiss[4]

[1] Department of Economics, University of Bath, Claverton Down, Bath, BA2 7AY, UK.

[2] Department of Geography, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK.

[3] PricewaterhouseCoopers, 1 Embankment Place, London, WC2N 6RH, UK.

[4] Paul Watkiss Associates, 18 Islip Road, Oxford, OX2 7SN, UK.

Revision 2 submitted to: *Climate Research (201212004R2)*

Main body words: 4494

21 September 2013

Corresponding author:

Robert L Wilby

Department of Geography

Loughborough University

Loughborough

Leicestershire

LE11 3TU

Email: r.l.wilby@lboro.ac.uk

Tel: +44 1509 223093

Abstract

Commodities such as food and manufactured goods, particularly those that rely on land and water, are increasingly recognised as being potentially sensitive to climate change on a global scale, suggesting that the international dimension is critical when considering future supply susceptibilities of import-dependent countries such as the UK. In this paper, we estimate embodied water imported to the UK for 25 economically significant and climate sensitive sub-sectors, then explore the current and future susceptibilities of these sub-sectors under climate change. In 2010, these products represented 31% of total UK imports by value ($), and 12.8 billion m^3 of embodied water. Of this rice, bovine and pig meat production, plastics and paper account for about 60% of the volume of water embodied in the import categories considered. By combining product-based water volume estimates with economic and climate model information we show how the UK could be increasingly susceptible to loss of these water supplements in the future. In doing so, we and provide an indication as to how countries that depend upon climate-sensitive imported resources can account for these dependencies in a systematic way. For example, international adaptation and development funding may be targeted to the securing of supplies from existing exporting countries, or trade relations may be encouraged with potential new suppliers who are likely to be less resource constrained.

1. Introduction

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

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

In fact, it is estimated that approximately 70% of the total water used in production and consumption in the UK (73 billion m^3/year) is imported from other countries in the form of water embodied in goods (Chapagain and Hoekstra, 2008). As such, the UK is one of the most water import-dependent nations in the world, alongside a small number of other North European countries and Middle Eastern states. This is a striking statistic, given that imports equate to just 15% of the UK economy, by value (ONS, 2011). Water use per unit of production in the UK is higher than many of the countries that currently export to the UK. Moreover, the UK is not able to substitute all foreign imports for domestic production, so the role of international trade and implied access to water is essential to maintaining current patterns of consumption.

Viewed another way, the total water volume needed to produce the goods and services consumed by the UK population, including the water embodied in imports, is 51% of the total national renewable water resource available (estimated to be 147 billion m^3/year) (Chapagain and Hoekstra, 2008). However, in parts of southeast England, actual and licensed water withdrawals from the environment already exceed sustainable levels (EA, 2009). Furthermore, pressures on UK water resources are projected to increase in the future, as a result of population growth (an expected 12% increase over the next 20 years [ONS, 2010]), economic growth, and climate change (ASC, 2012). Hence, the net flow in embodied water will also be an important, indirect determinant of the future health of UK freshwater ecosystems.

Given the inherent complexity of water accounting, few studies have attempted to quantify such water flows. Roson and Sartori (2010) use a computable general equilibrium (CGE) economic model to identify the effects that embodied water trading in agricultural products has on GDP under wet, middle and dry climate change scenarios of Mean Annual Runoff for 2050 in the Mediterranean region. They find that trade as an adaptation option facilitates increases in national GDP and net savings in embodied water. However, these gains are described as marginal; other public adaptation measures are highlighted as being required to more fully manage climate change-induced water resource constraints in the region. Konar et. al. (2013) also use CGE modelling to identify trade-related water savings, at the global scale, for rice, oil seeds (soy) and wheat, and use three crop productivity scenarios that account for precipitation, evapotranspiration and carbon dioxide (CO_2) fertilisation in 2030. They also find that there are water savings to be realised through international trade, and argue that these should be realised through reduction of existing trade barriers.

Whilst these studies identify potential trade effects at the regional and global scale the level of aggregation does not allow for analysis of national-scale responses within relevant sectors and sub-sectors. This paper therefore seeks to provide a more disaggregated analysis of potential climate change risks to the trade in embodied water, with the intention of facilitating a discussion of the alternative responses an importing country can introduce or promote by way of adaptation, additional to trade expansion. In Section 2 we outline our method for the identification and quantification of import sub-sectors that currently embody significant volumes of water, and for the evaluation of their susceptibility to future climate change risks. In Section 3 we present our results for 25 sub-sectors, and discuss these findings in Section 4. Section 5 then draws together our conclusions.

2. Data and Methods

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

2.1 Identification of significant sub-sectors

A sample of trade sub-sectors[i] was identified on the basis of a mapping process that plotted the economic significance of all sub-sectors (measured by import value) against the sensitivity to climate of the production activities within the sub-sector. Further details of this mapping process are provided in Watkiss and Hunt (2012). As a result of this mapping, UK import data (by value and 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

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

2.2 Quantification of embodied water in import sub-sectors

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

Figure 1 (lower panel) shows per tonne water consumption estimates for selected fuels, minerals, chemicals and manufactured products that are then used to calculate the total water consumption embodied in UK imports of these products. These single representative estimates for each product are used for imports from all selected countries of origin. **Figure 1** shows a higher estimate of 500 m^3/tonne for plastics but calculations were also performed using a lower estimate of 8 m^3/tonne. This large range reflects a variation in water use estimates for different forms of plastic or industrial processes. For example, whilst Morawicki, (2012) presents values of 500 m^3/tonne for polyethylene, polystyrene and polyvinyl chloride, Katsoufis (2009) estimate 8.7 m^3/tonne for polyethylene and 8.27 m^3/tonne for polypropylene.

2.3 Categorisation of exporting countries by current level of water scarcity

Current levels of water scarcity in countries exporting to the UK were classified using a widely recognised indicator of water stress (Falkenmark et al., 1989). Countries were defined as not water vulnerable (>2500 m^3/person/year), vulnerable (1700-2500 m^3/person/year), stressed (1000-1700 m^3/person/year), or water scarce (<1000 m^3/person/year).

2.4 Matching sub-sectoral embodied water with climate change risks

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

Climate risks were identified for one set of climate scenarios – reflecting data availability. However, it is well known that climate model scenarios show very different geographical patterns of change, particularly for precipitation, which is considered to be the most important driver of freshwater resources. Total uncertainty in global precipitation (and temperature) projections is conventionally divided into natural (internal) climate variability, climate model (structure and parameter) uncertainty, and radiative forcing (scenario) uncertainty. Depending on region, natural climate variability contributes 50-90% of total uncertainty over the next decade and remains the dominant source of uncertainty for 30 years (Hawkins and Sutton, 2010). Following the Foresight Futures project (Lewis et al., 2010), we refer to scenarios generated by an ensemble of Met Office Hadley Centre model HadCM3 experiments under SRES A1B emissions scenarios to 2040. Climate change scenarios were then matched geographically with the world regions from which UK imports originate. World commodity regions were categorised into standard climate zones using the Giorgi and Francisco (2000) regions.

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

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

3. Results

3.1 Current embodied water imports

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

Figure 2 shows total embodied water in all selected UK imports. It is evident that bovine meat production, plastics and paper production contribute the largest quantities of embodied water – in absolute terms – of the twenty-five import categories considered. Together, they account for about 40% of the 12.8 billion m^3 of embodied water in these twenty-five categories. Rice and other meat categories (poultry, pig and sheep) account for a further one-third of the total.

These results confirm findings of previous studies showing the high relative significance of the contribution of crops and livestock to the total water footprint of UK imports (Chapagain and Hoekstra, 2008; Chapagain and Orr, 2008; Feng et al., 2011). In the case of the crop imports studied, we estimate total virtual water flows to be about 4 billion m^3/year whilst the comparable figure for livestock is approximately 5 billion m^3/year. These compare with an aggregate of 43-46 billion m^3/year for embodied water in all crops and livestock – domestically produced and imported – for consumption in the UK (Chapagain and Hoekstra, 2008; Chapagain and Orr, 2008). To put these quantities into perspective, the total amount of water abstracted in the UK for all agricultural uses was 7.7 billion m^3 in 2006, equivalent to one-fifth of the water utilised in the production of agricultural products for export to the UK. Thus, it is clear that there is a substantial water deficit resulting from the patterns of embedded water in agricultural products consumed in the UK.

Estimates for UK industrial product imports are much less developed than for crops and livestock, reflecting their low importance in absolute terms in this regard. Based on crude assumptions, earlier studies claim that the embodied water in these imports is in the range of 17.2 to 20 billion m^3/year (based on statistics for 1997-2001) (Chapagain and Hoekstra, 2008; Chapagain and Orr, 2008). By way of comparison, total embodied water in domestic production of industrial products is less than 32 billion m^3/year (Yu et al., 2010). Even though our study focused on a few selected products, our estimates demonstrate that paper (1.7 billion m^3/year) and plastics (1.5 billion m^3/year) constitute a significant proportion of the total embodied volumes. We also compared the relative importance of these sectors utilising both the economic and water metrics, expressed in fractional terms. **Figure 3** shows that whilst the dominant economic sectors are energy and manufacturing, with the exception of paper and plastics, the major water consuming sectors are agricultural. This confirms the finding of previous research (Chapagain and Hoekstra, 2008).

3.2 Future embodied water imports

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

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

The five most important water uses, in volumetric terms, are rice, bovine meat, pig meat, plastics and paper and paperboard (see summary results for these sub-sectors in **Tables 5 to 9**, and full results in Supplementary **Tables S1 to S25**), though the high ranking of plastics reflects the use of the upper end of the per tonne water consumption range; use of the lower end value results in plastics being ranked 20th out of the 25 sub-sectors considered. Together, these commodities constitute about 60% of the 12.8 billion m^3 of the embodied water in our chosen imports. The total value ($) and water consumption (m^3) of the given commodity imported to the UK from key countries of origin was calculated along with total import value from all countries of origin for the year 2010. Note that our results for 2040 are specific to the chosen climate scenario and, that where no class is given in **Tables S1** to **S25**, information on the specific climate risk was not available.

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

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

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

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

4. Discussion

The five sub-sectors highlighted above provide several important insights. First, it is clear that they reflect diverse but economically important commodity groups that are sensitive to a range of climate change risks that vary in projected severity and likelihood. It is also clear from the scenario-based analysis that the susceptibility of production of UK imports of these commodities to changing patterns of precipitation is less certain than due to changes in temperature. However, it is also evident that these two sets of climatic variables need to be viewed together since production is potentially affected by inter-play of multiple climate – as well as non-climatic – pressures. Semenov et al. (2012), for example, show that both annual means and extreme weather events associated with precipitation and temperature are critical to wheat production. They also highlight the influence of technologies on agricultural productivity judged likely to interact with climatic factors in future time periods.

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

The static approach adopted contrasts with previous macro-economic analyses of embodied water in trade flows by making explicit the range of climate change effects to which the exporting country sub-sectors will need to consider and perhaps respond in their activities. The analysis is country-specific in both the fact that the value of these imports is important to the UK and that the country of origin is identified. Therefore, the analysis is designed to highlight that current trade partners of the UK may be impacted by climate change and that to retain this export market they may need to place increasing emphasis on water management. Alternatively, in order to maintain export earnings these countries may consider diversification in to less water-intensive industries. Conversely, the UK may wish to protect the supply of certain commodities from specific countries, or at certain cost levels, in which case the climate adaptation strategy would need to adopt an international dimension that encourages water management measures in the countries exporting these commodities to the UK. Alternatively, the UK could begin to consider developing new trade relationships with countries that are likely to be less negatively impacted by climate change and who would therefore provide either a lower-cost or more reliable supply of commodities.

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

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

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

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

5. Conclusions

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

Acknowledgements

Work for this paper was supported by the UK Committee on Climate Change.

References

Adaptation Sub-Committee (ASC), 2012. *Climate change – is the UK preparing for flooding and water scarcity?* Committee on Climate Change, London, 100pp.

Adger, W.N., S. Agrawala, M.M.Q. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. Pulwarty, B. Smit and K. Takahashi, 2007: Assessment of adaptation practices, options, constraints and capacity. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 717-743.

Allan, J.A. 1993. Fortunately there are substitutes for water: Otherwise our hydropolitical futures would be impossible. *Conference on Priorities for Water Resources Allocation and Management*, Overseas Development Agency, London.

Arnell, N.W. 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios, *Global Environmental Change*, **14**, 31-52.

Canals, L.M., Chapagain, A., Orr, S., Chenoweth, J., Anton, A. and Clift, R. 2010. Assessing freshwater use impacts in LCA, part 2: case study of broccoli production in the UK and Spain. *International Journal of Life Cycle Assessment*, **15**, 598-607.

Chapagain, A.K. and Hoekstra, A.Y. 2008. The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International*, **33**, 19-32.

Chapagain, A.K. and Orr, S. 2008. *UK Water Footprint: The Impact of the UK's Food and Fibre Consumption on Global Water Resources*. WWF, Godalming, UK, Vol. 1.

Chi N. K. 2008. *Water related industrial development and industrial wastewater, Vietnam Water Sector Review*, Government of Vietnam.

Department for Environment, Food and Rural Affairs (Defra), 2012. *The UK Climate Change Risk Assessment 2012 Evidence Report*. HM Government, London, 488pp.

Environment Agency (EA), 2009. *Water for people and the environment*. Water resource strategy for England and Wales. Environment Agency, Bristol.

Environwise, 2003. *Managing water use in speciality chemical's manufacture: a signposting guide*. Didcot, UK, 47pp.

Falkenmark, M., Lundquist, J., Widstrand, C., 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. *Natural Resources Forum*, **13**, 258–267.

Feng, K., Hubacek, K., Minx, J., Siu, Y.L., Chapagain, A., Yu, Y., Guan, D. and Barrett, J. 2011. Spatially explicit analysis of water footprints in the UK. *Water*, **3**, 47-63.

Foresight Futures, 2011. *International Dimensions of Climate Change*. Final Project Report. The Government Office for Science, London, 129pp.

Gerbens-Leenes, W., Hoekstra, A. Y. and van der Meer, T. 2008. The water footprint of energy carriers. Proceedings of the 13th IWRA World Water Congress, Montpelier, September 2008.

Giorgi, F. and Francisco, R. 2000. Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HadCM2 coupled AOGCM. *Climate Dynamics*, **16**, 169-182.

Hawkins, E. and Sutton, R. 2010. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37**, 407-418.

Hoekstra , A.Y. 2003. *Virtual water trade Proceedings of the International Expert Meeting on Virtual Water Trade*, Edited by A.Y. Hoekstra, February 2003 Value of Water Research Report Series No. 12.

Hoekstra, A.Y. and Hung, P.Q. 2002. *Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade*. Value of Water Research Report Series No. 11, UNESCO-IHE, Delft, the Netherlands.

International Mining, 2007. *Minimizing water use and its pollution*. July 2007.

Katsoufis, S. (2009) *Cradle-to-Gate Water Footprint Analysis of Borealis Group Polyolefin Value Chain*. Master of Science Thesis. Stockholm, September 2009

Konar, M., Dalin, C.,. Hanasaki, N. Rinaldo, A. and I. Rodriguez-Iturbe (2012) Temporal dynamics of blue and green virtual water trade networks. *Water Resources Research*, Vol. 48.

Konar, M., Hussein, Z., Hanasaki, N., Mauzerall, D. L., and I. Rodriguez-Iturbe (2013) Virtual water trade flows and savings under climate change. *Hydrology and Earth System Sciences*, **10**, 67-101.

Kumar, V. and Jain, S.K. 2007. Status of virtual water trade from India. *Current Science*, **93**, 1093-1099.

Lewis K., Witham, C. and McCarthy, R. 2010. *Physical Resources and Commodities and Climate Change*. Report for Foresight International Dimensions of Climate Change. June 2010.

Mader, T. L. 2003. Environmental stress in confined beef cattle. *Journal of Animal Science* 81:E110–E119.

Mekonnen, M.M. and Hoekstra, A.Y. 2011. *National water footprint accounts: the green, blue and grey water footprint of production and consumption*, Value of Water Research Report Series No. 50, UNESCO-IHE, Delft, the Netherlands. http://www.waterfootprint.org/Reports/Report50-NationalWaterFootprints-Vol1.pdf

Morawicki, R.O. 2012. *Handbook of Sustainability for the Food Sciences*. Wiley Blackwell, Chichester.

Office for National Statistics (ONS), 2010. *Projected populations of the constituent countries of the UK*. Environmental Accounts 2010: February 2010 Update, London.

Office for National Statistics (ONS), 2011. *United Kingdom National Accounts: The Blue Book. 2011 Edition*. Newport.

Pretty, J. N., Ball, A.S., Lang T. and Morison, J.I.L. 2005. Farm costs and food miles: An assessment of the full cost of the UK weekly food basket. *Food Policy*, **30**, 1-19.

Rosegrant, M., Cai, X., and Cline, S. 2002. *World water and food to 2025* (First Edition), International Food Policy Research Institute, Washington, DC, USA.

Roson, R., and Sartori, M. 2010. *Water Scarcity and Virtual Water Trade in the Mediterranean*, IEFE Working Papers Series – ISSN 1973-0381, Milan, Bocconi University n.42.

Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer , J. and Schaphoff, S. 2008. Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, **44**, W09405.

Semenov, M.A., Mitchell, R.A.C., Whitmore, A.P., Hawkesford, M.J., Parry, M.A.J. and Shewry, P.R. 2012. Shortcomings in wheat yield predictions. *Nature Climate Change*, **2**, 380-382.

Seneviratne, M. 2007. *A Practical Approach to Water Conservation for Commercial And Industrial Facilities*, Butterworth-Heinemann, Oxford, UK.

Tata Steel, 2012. *Compliance to environmental clearance conditions of Joda East Iron Mine*, Tata Steel Limited, India.

United Nations Environment Programme (UNEP), 2008. *Vital Water Graphics - An Overview of the State of the World's Fresh and Marine Waters*. 2nd Edition. UNEP, Nairobi, Kenya.

United Nations Standing Committee on Nutrition, 2012. *Climate change and nutrition security*. World Health Organisation, Geneva, 12pp.

United Nations, 2004. *World Population to 2300*. Department of Economic and Social Affairs Population Division, New York.

Verma, N.K. 2011. *Environmental Management in Pharmaceutical Industry and Charter on Corporate Responsibility for Environmental Protection*. Awareness Programme on Environment & Hazard Management in Pharmaceutical & Bulk Drug Industry, Ankaleshwar. 31st January, 2011 http://www.hrdpnet.in/live/hrdpmp/hrdpmaster/hrdpasem/content/e8451/e8981/e31428/e32044/e32111/eventReport32118/EnvironmentalManagementinPharmaceuticalIndustry.pdf

Watkiss, P. and Hunt, A. 2012. *Filling the gaps around the CCRA: Assessing the economic impacts of indirect, international and major risks*. Paul Watkiss Associates, 84pp.

Yu, Y., Hubacek, K., Feng, K. and Guan, D. 2010. Assessing regional and global water footprints for the UK. *Ecological Economics*, **69**, 1140-1147.

Table 1 Sub-sector commodities with country-specific example data of per tonne embodied water in 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)

Table 2 Examples of climate risks affecting production in countries exporting to the UK. Adapted 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)

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

		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

Table 3b. Classes of water availability (lower box) based on current (2010) water scarcity categories 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)

[iv] http://www.unep.org/dewa/vitalwater/jpg/0221-waterstress-EN.jpg

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 – m3/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.

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

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									

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

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						

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

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						

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

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							
528 India	20,208	B1	B3	B1	A2	A2	C1

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

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							
532 India	7,458,270	B1	B3	B1	A2	A2	C1

533

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

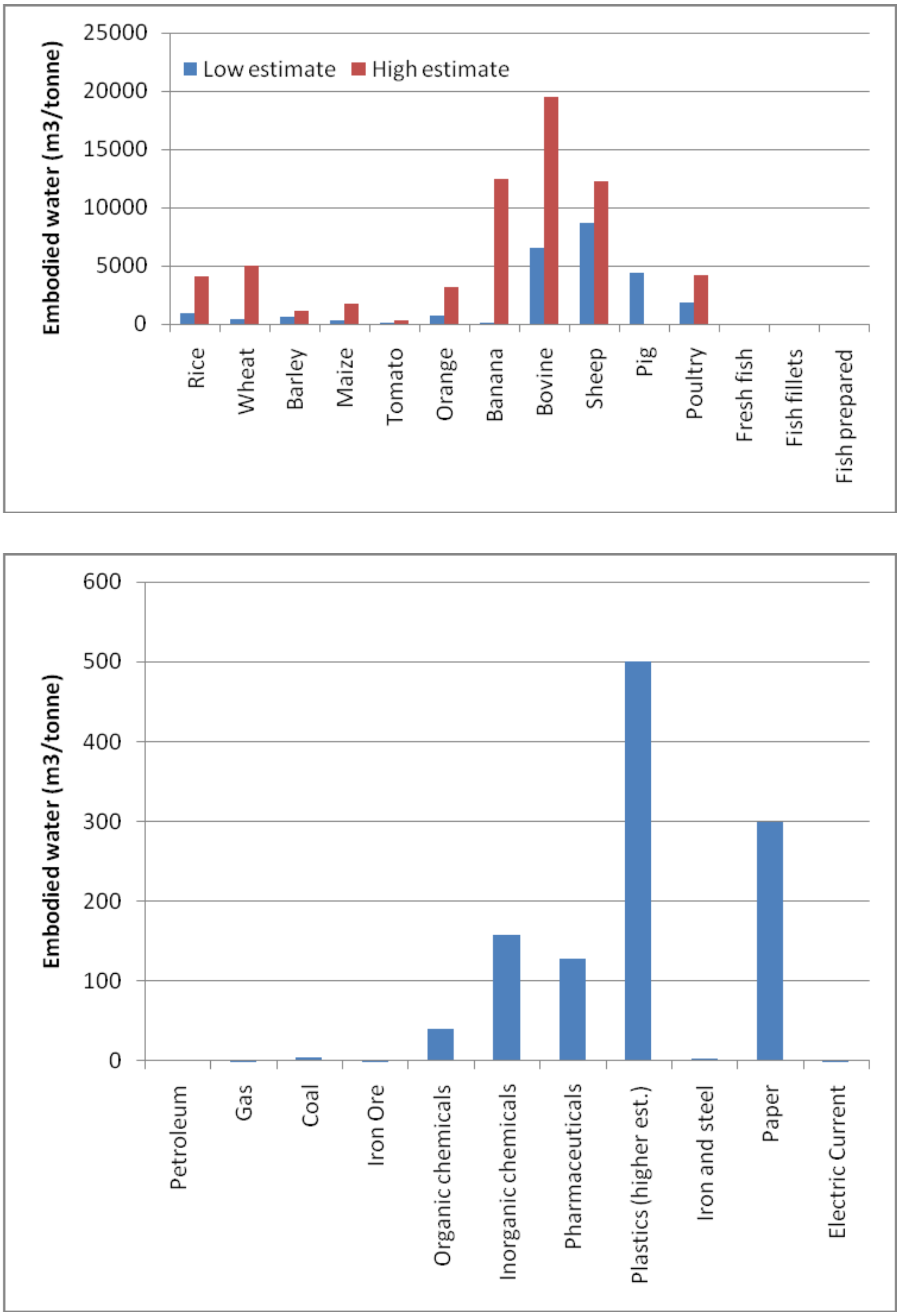

Figure 2 Total water volumes embodied in selected UK imports (2010)

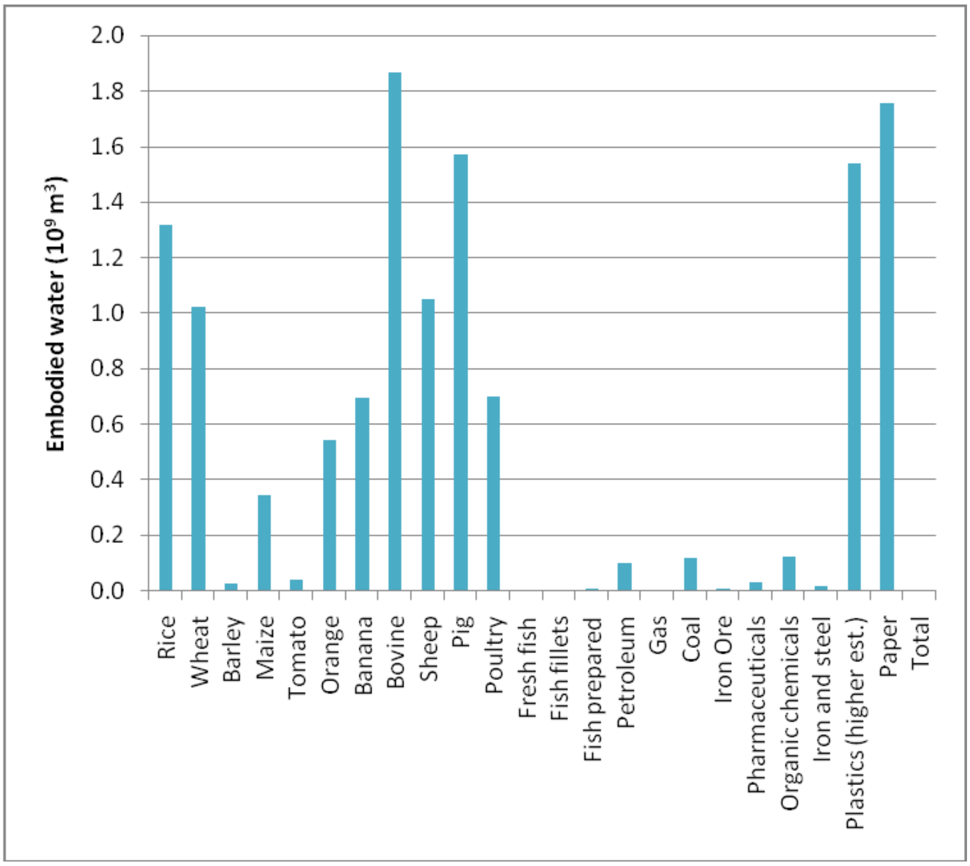

Figure 3 Fractional economic value and water consumption for selected UK imports in 2010