

# Today's virtual water consumption and trade under future water scarcity

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## Abstract

The populations of most nations consume products of both domestic and foreign origin, importing together with the products the water which is expended abroad for their production (termed 'virtual water'). Therefore, any investigation of the sustainability of present-day water consumption under future climate change needs to consider the effects of potentially reduced water availability both on domestic water resources and on the trades of virtual water. Here we use combinations of Global Climate and Global Impact Models from the ISI-MIP ensemble to derive patterns of future water availability under the RCP2.6 and RCP8.5 greenhouse gas (GHG) concentrations scenarios. We assess the effects of reduced water availability in these scenarios on national water consumptions and virtual water trades through a simple accounting scheme based on the water footprint concept. We thereby identify countries where the water footprint within the country area is reduced due to a reduced within-area water availability, most prominently in the Mediterranean and some African countries. National water consumption in countries such as Russia, which are non-water scarce by themselves, can be affected through reduced imports from water scarce countries. We find overall stronger effects of the higher GHG concentrations scenario, although the model range of climate projections for single GHG concentrations scenarios is in itself larger than the differences induced by the GHG concentrations scenarios. Our results highlight that, for both investigated GHG concentration scenarios, the current water consumption and virtual water trades cannot be sustained into the future due to the projected patterns of reduced water availability.

 Online supplementary data available from [stacks.iop.org/erl/9/074007/mmedia](http://stacks.iop.org/erl/9/074007/mmedia)


Keywords: sustainable water consumption, climate change, virtual water trades, future water scarcity

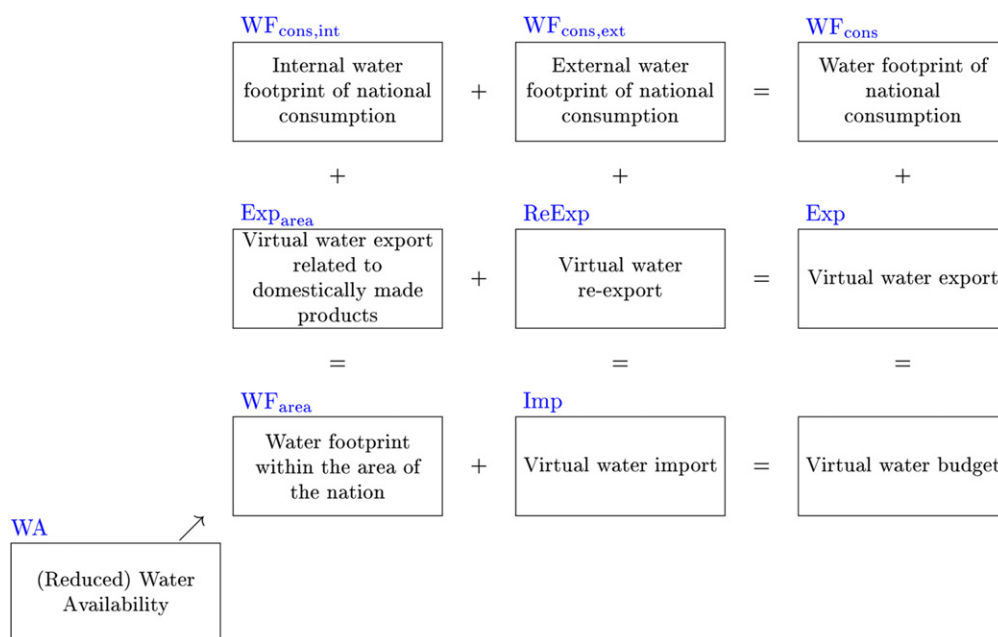
## 1. Introduction

Since its conception more than ten years ago (see Hoekstra 2009), the water footprint of a nation has been used increasingly as a means of synthesizing a nation's water needs (Hoekstra and Hung 2005, Hoekstra and Chapagain 2006, Chapagain and Hoekstra 2008, Mekonnen and Hoekstra 2011, Hoekstra and Mekonnen 2012). This measure

explicitly accounts for the trades of goods between nations and the water which is consumed for their production. Water traded in this way is referred to as 'virtual water' and constitutes a significant portion of global water consumption (e.g., about one fifth of the global water footprint relates to production for export, Hoekstra and Mekonnen 2012).

The footprints of virtual water consumption and trades are interrelated through a simple accounting scheme, which is illustrated in figure 1 (see section 2 for details). For the national and gridded water footprints and virtual water trades between nations in Hoekstra and Mekonnen (2012), this accounting is done separately for a large number of agricultural and industrial products as well as the footprints of

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**Figure 1.** Accounting framework and different water footprints with mathematical notation. Adapted from Hoekstra and Mekonnen (2012).

domestic water supply. Together these combine to the total national water footprints. Commonly the accounting distinguishes green and blue water, where green water refers to the evaporated water over rain-fed agricultural areas and blue water refers to water extracted from rivers, lakes and groundwater. The third category, polluted or grey water, is not considered in the present analysis.

Water availability as a precondition for water consumption has been the subject of earlier studies, see e.g. Oki and Kanae (2006) for a global analysis of present-day blue water availability and scarcity, which highlights extended water scarce regions mainly in the Eurasian and North American mid latitudes. Gerten *et al* (2011) find consistent patterns for the future and express water stress as a function of climate, population development and dietary needs. The pattern of future water scarcity is also found by Portmann *et al* (2013) in terms of decreased groundwater recharge from simulations of the ISI-MIP ensemble (Warszawski *et al* 2014), which combines Global Climate Models (GCMs) with hydrological Global Impact Models (GIMs). Schewe *et al* (2014) investigate projections of the number of people affected by decreased water availability from river runoff, reconfirming the scarcity patterns of the other studies. Climate change impacts on irrigation in Elliott *et al* (2013) provide consistent results. Furthermore, Hoekstra *et al* (2012) find a strong seasonal dependence of water scarcity for the main river basins across the globe.

However, all these studies were local in the sense that they compared local water availability to local water needs. They thus neglected the potential of virtual water trades to compensate for local water deficits. Actually modelling future water trades is extremely difficult and involves many assumptions regarding climate change, population and economic development, technological advances, dietary changes etc. (e.g. Erzin and Hoekstra 2014). For instance, Dalin *et al*

(2012) provide an analysis based on a statistical model of the virtual water trade network to derive global information on the general network structure in the future. Nelson *et al* (2014) use a model chain of climate, crop and global economic models to investigate economic responses in agriculture, but do not resolve the country scale and consider only a limited set of crops. Konar *et al* (2013) model future trades explicitly, but their calculations are restricted to a small number of crops.

In contrast, our study targets the overall consumption of (virtual) water within each nation by investigating whether the consumption and trade patterns of virtual water as they exist today can be sustained under constraints from future climates, in particular considering the effect of reduced water availability. We explicitly limit our investigation to this climatic constraint. Our research design thereby does not rely on projections of socio-economics or future water demand and allows for an isolated consideration of future limitations from an altered freshwater distribution across the globe. To this end we link future climate projections from the ISI-MIP ensemble (Warszawski *et al* 2014) to present-day data of national water footprints and virtual water trades (Hoekstra and Mekonnen 2012).

In the following, section 2 details our accounting approach and the virtual water data that we use. Section 3 introduces the database of present-day and future water availability. Results are presented in section 4 and discussed in section 5, which also concludes our study.

## 2. Virtual water accounting and data

If the future amount of available water in a nation is reduced by climate change and falls below the requirements of production, then this production can no longer be sustained. On

the other hand, the effect of increased water availability is much harder to predict, since production is not limited by water availability only. In many instances, the market demand for a product is the main limiting factor (Mankiw 2014). Since our focus is the compatibility of present-day water consumption and trades with future water availability within an otherwise unchanged setting, we restrict our analysis to the effects of reduced future water availability. Beneficial effects of the projected spatially redistributed and thereby in certain regions increased water availability are not taken into account, since these depend not only on climate but also on future economic and political choices. Despite this omission, our analysis allows us to investigate the sustainability of present-day water trades with regard to future patterns of water availability, as described below.

### 2.1. Present-day virtual water budgets

In the accounting scheme of figure 1, the left column shows that the water footprint within the nation's area,  $WF_{area}$ , consists of the water used for domestic production and consumed by the nation's population (internal water footprint of national consumption,  $WF_{cons,int}$ ) as well as the virtual water in domestic products which are exported to other countries,  $Exp_{area}$ . Similarly, the imports of virtual water  $Imp$  (middle column), split into the external water footprint of national consumption  $WF_{cons,ext}$ , that is the virtual water which is imported for consumption by the nation's population, and the imported and re-exported virtual water,  $ReExp$ , where  $ReExp$  is a simple closing entry in the water budgeting (Mekonnen and Hoekstra 2011). Total national consumption (top row) consists of internal and external water footprints,  $WF_{cons} = WF_{cons,int} + WF_{cons,ext}$ .

We use the present-day (1996–2005) national water footprints and bi-lateral virtual water trades from Hoekstra and Mekonnen (2012) for blue and green water, which are partly available from the WaterStat database at [www.waterfootprint.org](http://www.waterfootprint.org) (accessed December 2013). This database poses several challenges to our analysis.

First, it does not contain all components of the virtual water accounting for all countries, especially the footprints of consumption are not available for several countries.

Second, while for industrial products the national consumption footprint was derived as  $WF_{cons} = WF_{area} + Imp - Exp$  (top-down approach), for agricultural products (which account for the bulk of the water footprints globally, see figure S1 in the Supplementary Materials) the virtual water trades are determined for each product individually and summed up to obtain the national consumption (bottom-up approach, see Hoekstra and Mekonnen 2012 for details). As described in van Oel *et al* (2009), top-down accounting is sensitive to inaccuracies in trade data, especially for nations with large trade volumes relative to their domestic production, while bottom-up accounting relies directly on consumption data. Inconsistent data streams from incomplete or inaccurate reporting on production, consumption and international trade per country can lead to different footprints from top-down and bottom-up

accounting, respectively. In particular, for the bottom-up accounting of agricultural products, the budget of the individual virtual water components can be unclosed, which is not the case for the top-down derived virtual water budget of industrial products. Different product categorisations in different data streams add to the accounting challenges and may lead to double counting of the virtual water in different products, although this has been eliminated as far as possible (see Hoekstra and Mekonnen 2012 and references therein). Inconsistent data bases lead for a few countries to violation of the required inequalities  $WF_{cons,ext} \leq Imp$  and  $WF_{cons,int} \leq WF_{area}$  (see figure 1).

A further limitation of this database lies in the lack of temporal dynamics. We therefore cannot consider the temporal representativity of the 1996–2005 averages in our analysis, which might partly explain the detected inconsistencies. While earlier studies (e.g. Carr *et al* 2012) show that the network of virtual water flows has evolved substantially over time with many trade connections appearing and disappearing every year, one should keep in mind the challenges that already arise when computing the here used decadal averages. These challenges are even more relevant for shorter time scales and potentially compromise a thorough assessment of the temporal representativity. In our study we take the water footprint database as an 'average snapshot' of the present day situation and investigate whether this 'average snapshot' could as well exist under future water availability patterns.

Since our accounting requires knowledge of all components, we can only analyze the 173 countries with complete records. Removing the incomplete countries, however, introduces inconsistencies in the remaining countries, for example if the external consumption of a country depends substantially on the imports from one of the countries which are removed. This does not limit the investigation of local water demand versus local water availability, but affects the national water consumption through potentially inconsistent imports. For most countries, the differences between their imports from all nations and their imports from only these nations with complete records are below 10%. Countries with larger differences are listed in table 1. We do not exclude these countries from the analysis but highlight them by a stippling in the maps of section 4. Figure S2 in the Supplementary Materials provides histograms of the number of countries per class of relative adjustment and their respective shares of total imports and exports. Globally, the import/export adjustments range between 4% and 8%.

After calculating the adjusted imports  $Imp^{adj}$  and exports  $Exp^{adj}$  of each nation considering only the trades between nations with complete records, we recompute the blue and green water footprints of total national consumption as  $WF_{cons}^{adj} = WF_{area} + Imp^{adj} - Exp^{adj}$  (the top-down approach). This ensures closed virtual water budgets.

We finally balance-adjust the internal and external footprints of national consumption ( $WF_{cons,int}$  and  $WF_{cons,ext}$ ) such that they balance the adjusted total footprints of national consumption  $WF_{cons}^{adj}$  while keeping their ratio unchanged. We further ensure that  $WF_{cons,int}$  and  $WF_{cons,ext}$  do not exceed the

**Table 1.** Countries with differences between original and adjusted virtual imports >10% (green or blue water). These countries are highlighted in the maps of section 4.

| Country                                   | Blue imports (Mm <sup>3</sup> yr <sup>-1</sup> ) |          | Green imports (Mm <sup>3</sup> yr <sup>-1</sup> ) |          |
|---|--|----------|---|----------|
|   | Complete   | Adjusted | Complete  | Adjusted |
| Australia                                 | 1181   | 1148     | 6452  | 5718     |
| Brunei Darussalam                         | 4470   | 806      | 15483   | 2040     |
| Burma                                     | 71   | 58       | 1197  | 1049     |
| Cambodia                                  | 127  | 98       | 632   | 488      |
| Eritrea                                   | 445  | 248      | 1628  | 1265     |
| Iran (Islamic Republic of)                | 1496   | 1330     | 16625   | 16509    |
| Jordan                                    | 902  | 668      | 4933  | 4706     |
| Lebanon                                   | 648  | 569      | 3368  | 3263     |
| Maldives                                  | 59   | 54       | 241   | 213      |
| Pakistan                                  | 2797   | 2086     | 14521   | 14135    |
| Seychelles                                | 19   | 18       | 101   | 81       |
| Solomon Islands                           | 7  | 7        | 161   | 137      |
| Suriname                                  | 12   | 11       | 96  | 93       |
| Syrian Arab Republic                      | 802  | 508      | 3240  | 2986     |
| The former Yugoslav Republic of Macedonia | 147  | 115      | 729   | 551      |
| Uganda                                    | 108  | 107      | 1192  | 1067     |
| Yemen                                     | 1615   | 898      | 19896   | 4678     |

within-area footprint  $WF_{area}$  and imports  $Imp$ , respectively. Details and further discussion are provided in section S3, Supplementary Materials. We use only the adjusted footprints and therefore omit the 'adj'-superscripts.

The effects of all adjustments (for removal of incomplete countries, unclosed water balances, violated inequalities) on the water balance components are substantial for a number of countries, reflecting the inconsistencies of the data sources from which the water footprints are derived. Differences between adjusted and original consumption footprints are below 10% for less than a third of all countries and below 50% for approximately 80% of all countries (see table 2). In terms of volume, some 80% of most components of the global footprints are affected by adjustments below 25%. Figure S3 in the Supplementary Materials shows that adjustments are of both signs and globally correspond to volume adjustments of below 10% (except for blue water and  $WF_{cons,ext}$ , for which adjustments amount to 23%). Large relative adjustments concern mainly smaller volumes and do not affect the main water flows across the globe, which are concentrated between a limited number of trading nations (Konar *et al* 2011). See section S3 in the Supplementary Materials for details. Furthermore, since we are only interested in climate-induced changes of water consumption footprints, their absolute magnitude is less relevant for our purpose.

**Table 2.** Numbers of nations and the corresponding percentage of the total water footprint (in parentheses) in different classes of relative differences between the national consumptions before and after the adjustments.

| #nations (%age of total WF) per class of relative differences before/after adjustment |                        |                        |              |              |              |             |             |
|---|------------------------|------------------------|--------------|--------------|--------------|-------------|-------------|
| Water   | Footprint              | < 10%                  | 10%-25%      | 25%-50%      | 50%-100%     | >100%       |             |
| Blue  | WF <sub>cons</sub>     | 45<br>(53.3)           | 49<br>(24.7) | 48<br>(10.9) | 25<br>(10.9) | 6<br>(0.2)  |             |
|   | WF <sub>cons,ext</sub> | 44<br>(24.7)           | 42<br>(32.2) | 50<br>(22.5) | 31<br>(20.2) | 6<br>(0.4)  |             |
|   | WF <sub>cons,int</sub> | 31<br>(59.0)           | 52<br>(23.3) | 47<br>(8.4)  | 23<br>(9.1)  | 10<br>(0.2) |             |
|   | Green                  | WF <sub>cons</sub>     | 56<br>(33.7) | 53<br>(45.4) | 41<br>(15.7) | 14<br>(4.7) | 9<br>(0.5)  |
|   |                        | WF <sub>cons,ext</sub> | 42<br>(35.1) | 49<br>(31.2) | 50<br>(25.0) | 25<br>(8.3) | 7<br>(0.3)  |
|   |                        | WF <sub>cons,int</sub> | 54<br>(32.0) | 55<br>(47.4) | 38<br>(15.0) | 14<br>(5.1) | 12<br>(0.5) |

## 2.2. Water footprinting under reduced future water availability

Depending on the region, projected water availability is either increased or reduced. While a reduced water availability imposes a direct climatic constraint on production, the effects of increased water availability depend on many non-climatic factors determining how the additional water is used. Since these are beyond the scope of our study, we consider effects of reduced water availability only. In our accounting, water flows can either be maintained or need to be reduced, but they never increase.

Any reduced future water availability,  $WA(fut)$ , hits the accounting scheme at the lower left corner (figure 1), if the available water is less than the present-day water footprint within the area of the nation,  $WF_{area}(now)$ . We assume that a nation manages its water resources sustainably in that it does not consume more water than available within its area, i.e.  $WA(fut) \geq WF_{area}(fut)$ . This assumption excludes the possibility of over-consumption, e.g. by depleting groundwater for irrigation. Note, however, that some nations use their blue water resources unsustainably under present-day conditions (see section 4) and that our accounting for the future in these countries therefore reflects effects both of climate change and their unsustainable present-day consumption.

In order to propagate a potentially reduced within-area footprint  $WF_{area}(fut)$  through the other components of the accounting scheme, we further make the conservative assumption that a nation will always prioritize the consumption of its population over its water exports. As mentioned before, only effects of reduced water availability propagate, therefore in our accounting virtual water exports and imports never increase.

Beginning in the left column of figure 1, assume that a reduced future water availability  $WA(fut)$  forces a nation to reduce its  $WF_{area}$ . The nation will compensate for this reduction by reducing, in the first place, the virtual water exports related to domestically made products,  $Exp_{area}$ . Only if the



forced reduction is larger than the exports can compensate for, i.e. that even stopping all exports does not suffice to achieve the forced reduction, the internal water footprint of national consumption,  $WF_{\text{cons,int}}^i$ , is reduced as well.

The  $WF_{\text{area}}^i$  of nation  $i$  thus becomes

$$WF_{\text{area}}^i(\text{fut}) = \min(WF_{\text{area}}^i(\text{now}), WA(\text{fut})), \quad (1)$$

and the  $WF_{\text{cons,int}}^i$  becomes

$$WF_{\text{cons,int}}^i(\text{fut}) = \min(WF_{\text{cons,int}}^i(\text{now}), WF_{\text{area}}^i(\text{fut})). \quad (2)$$

Potential future exports  $Exp_{\text{area}}^i$  from nation  $i$  are therefore

$$Exp_{\text{area}}^i(\text{fut}) = WF_{\text{area}}^i(\text{fut}) - WF_{\text{cons,int}}^i(\text{fut}). \quad (3)$$

By construction,  $Exp_{\text{area}}^i(\text{fut}) \leq Exp_{\text{area}}^i(\text{now})$ . The potentially reduced export capacity  $Exp_{\text{area}}^i(\text{fut})$  of a given nation reduces the amount of virtual water that another nation can import from the given nation. We assume that the exports from the given nation to all its trading partners are reduced by the same share such that the total exports correspond to the reduced export capacity.

The potential imports of virtual water of nation  $i$  from nation  $j$ ,  $Imp^{i,j}(\text{fut})$ , are therefore

$$Imp^{i,j}(\text{fut}) = \frac{Exp_{\text{area}}^j(\text{fut})}{Exp_{\text{area}}^j(\text{now})} Imp^{i,j}(\text{now}). \quad (4)$$

By construction,  $Imp^{i,j}(\text{fut}) \leq Imp^{i,j}(\text{now})$ . Knowing thereby the potentially reduced virtual water trades between all nation pairs under future reduced water availability, we are able to compute the total virtual water imports  $Imp(\text{fut})$  for all nations (bottom centre in figure 1).

$$Imp^i(\text{fut}) = \sum_{j \neq i} Imp^{i,j}(\text{fut}). \quad (5)$$

By construction,  $Imp^i(\text{fut}) \leq Imp^i(\text{now})$ . For the imports we apply the same reasoning as above, namely that the nation will, if its imports are reduced, in the first place reduce its re-exports  $ReExp$  and try to maintain its external footprint of national consumption,  $WF_{\text{cons,ext}}^i$ .

$$WF_{\text{cons,ext}}^i(\text{fut}) = \min(WF_{\text{cons,ext}}^i(\text{now}), Imp^i(\text{fut})), \quad (6)$$

$$ReExp^i(\text{fut}) = Imp^i(\text{fut}) - WF_{\text{cons,ext}}^i(\text{fut}). \quad (7)$$

The future total virtual water exports of nation  $i$  become

$$Exp^i(\text{fut}) = Exp_{\text{area}}^i(\text{fut}) + ReExp^i(\text{fut}). \quad (8)$$

By construction,  $Exp^i(\text{fut}) \leq Exp^i(\text{now})$ . With these components we are finally able to calculate the total water footprint of national consumption under future water scarcity,

$$WF_{\text{cons}}(\text{fut}) = WF_{\text{area}}(\text{fut}) + Imp(\text{fut}) - Exp(\text{fut}) \quad (9)$$

$$= WF_{\text{cons,int}}(\text{fut}) + WF_{\text{cons,ext}}(\text{fut}). \quad (10)$$

Since by construction  $WF_{\text{cons}}(\text{fut})$  does not account for the projected increases of water availability in several regions, it does not represent the actual future water footprint of national

consumption. Of more interest in our study therefore is the change from  $WF_{\text{cons}}(\text{now})$  to  $WF_{\text{cons}}(\text{fut})$ , which at country scale provides a measure of adaptation needs to the effects of water scarcity.

### 3. Water availability data

#### 3.1. Present-day water availability

For the present-day water availability, we follow the approaches in Gerten *et al* (2011) and Hoekstra *et al* (2012) for blue water, and the definition in Hoekstra and Mekonnen (2012) for green water.

Since observed runoff corresponds to the available blue water minus the consumed blue water (i.e. the net withdrawn water or blue water footprint), we combine maps of observed runoff and blue water footprints to obtain a map of blue water availability. As in Hoekstra *et al* (2012), we use the multi-year average field from the Composite Runoff V1.0 database (Fekete *et al* 2002) for the observed runoff and add a 74% of the gridded blue water footprint field from Hoekstra and Mekonnen (2012). The 74% correspond to the ratio of the global blue water footprint between 1975, which is the central year of the Composite Runoff average, and 2000, which is the central year of the 1996-2005 period for which the gridded blue water footprint is estimated (see Hoekstra *et al* 2012 for details). Note that the runoff field corresponds to a slightly earlier period compared to the water footprint data. However, given that we are dealing with multi-year averages, we do not expect large effects from this discrepancy. If anything, this discrepancy makes our analysis more conservative, since we derive a blue water availability which is less affected by climate change by a few years.

In order to obtain the blue water availability of the nations, we follow Gerten *et al* (2011) in that we redistribute the total corrected runoff of a river basin with weights according to the discharge pattern within that basin. This assigns higher blue water availability to grid cells with higher discharges while at the same time avoiding double counting of up-stream water. We use the TRIP river flow-paths and basins to compute discharge from runoff (Oki and Sud 1998). This redistributed runoff is summed over the nations' areas to yield the nations' blue water availability. As in Hoekstra *et al* (2012) and references therein, we assume that, when securing environmental flow requirements, a 20% of these national runoff sums is available for consumption.

Note that due to lacking baseline data we only consider surface water (runoff) for blue water availability, while the blue water footprints consist of both surface and groundwater extraction. We therefore systematically underestimate blue water availability, but one should keep in mind that groundwater extraction occurs often at higher rates than can be compensated for by natural recharge (Wada *et al* 2010). Groundwater extraction therefore rarely corresponds to sustainable use of resources and within the long-term focus of our study, surface water provides the main source for sustainable blue water consumption. The omission of

groundwater for blue water availability therefore makes our estimate of future water availability conservative.

For green water, we equate the present-day water availability of a nation with its within-area green water footprint, corresponding to the multi-year annual average of evapotranspiration over crop and pasture regions (Hoekstra and Mekonnen 2012). This ensures a consistent accounting across all countries despite e.g. differing cropping seasons.

### 3.2. Future water availability from ISI-MIP

In order to reduce the effect of model biases on the future water availability estimates, we compute future availabilities of green and blue water by adding to the present-day availabilities the  $\Delta$ -changes (future minus present-day availability) of evapotranspiration and discharge-scaled runoff, respectively. We compute the present-day climate from the ISI-MIP fast track simulations (Warszawski et al 2014) with historical forcing, considering the 30-year average of 1975–2004. The future climates are derived from future ISI-MIP projections, considering the 30-year average of 2070–2099. These future projections are forced with two greenhouse gas (GHG) concentrations scenarios, the peak-and-decline scenario RCP2.6 and the rising GHG concentrations scenario RCP8.5 (Moss et al 2010), which frame the spread of the GCM projections of the 5th phase of the Coupled Model Inter-comparison Project (CMIP5, see Taylor et al 2012). ISI-MIP employs the Shared Socio-economic Pathways (SSPs, see O'Neill et al 2014) as socio-economic forcing for the GIMs. However, in order to investigate the constraints from climate change only, we select projections with fixed present-day socio-economic forcings.

From ISI-MIP, we use 35 simulations (combinations of five GCMs and seven GIMs) for each RCP scenario and the present-day simulations. The  $\Delta$ -changes are computed as the difference of the future minus the historical water availability. For each RCP scenario, we derive three cases from its 35 simulations by computing the 10th percentile, the median and the 90th percentile of the 35 $\Delta$ s for each grid cell. We refer to the three cases as dry, median and wet, respectively. Further details of the selected simulations are provided in section S1 of the Supplementary Materials.

The  $\Delta$  patterns of these three cases are summed at the country level taking grid cell areas into account. For the green water  $\Delta$ s, the grid cells are further weighted with the fractions of agricultural area in the grid cells (fractions of crop plus pasture from Monfreda et al 2008).

## 4. Results

We analyze two ratios, the scarcity ratio and the sustainability ratio. The *scarcity ratio* (Hoekstra et al 2012) consists of the present-day within-area water footprint  $WF_{area}(now)$  of a nation divided by the respective water availability for present-day and future climates,  $WF_{area}(now)/WA(now)$  and  $WF_{area}(now)/WA(fut)$ , respectively. We compute national water scarcities on an annual basis, due to the absence of data

to calculate water scarcities at higher temporal resolution at the national level. This ratio ranges from 0 to infinity, with higher values corresponding to scarcer situations. The value of 1 separates water scarce from non-water scarce nations.

The *sustainability ratio* consists of the future national consumptions divided by the present-day national consumptions,  $WF_{cons}(fut)/WF_{cons}(now)$ . Note that we thereby use the term ‘sustainability’ in a narrow sense, referring only to the amount of available water for production and trade, and excluding many of the common social, economic and environmental dimensions. The sustainability ratio ranges from 0 to 1, where 1 means that the consumption is not affected by future water scarcity anywhere and 0 means that the entire consumption needs to be re-organized, due to either within-area or abroad water scarcity. We produce these ratios for green and blue water separately as well as for the sum of both, to account for possible compensation between the two (e.g., a lack of green water for agriculture can be compensated by irrigation from blue water resources).

### 4.1. Climatic constraints on national within-area water footprints

Figure 2 shows the scarcity ratios under present-day conditions. For blue water, already under present-day conditions countries around the Mediterranean and Central Asia consume more water than available from a sustainable blue-water use. For green water, the present-day water availability per definition equals the present-day within-area water footprint, yielding a scarcity ratio of 1. The maps of the scarcity of blue and green water together visually average the individual maps of green and blue water scarcity.

The constraints on the within-area footprint of blue water become even more severe under future conditions in these regions (top half of figure 3), consistent with related studies (Oki and Kanae 2006, Gerten et al 2011, Hoekstra et al 2012). The strongest changes occur for the dry case, but even here most of the countries with future water scarcity are already water scarce (or at least close to) under present-day conditions. The future scarcity patterns result from both the present-day water management and future constraints on water availability.

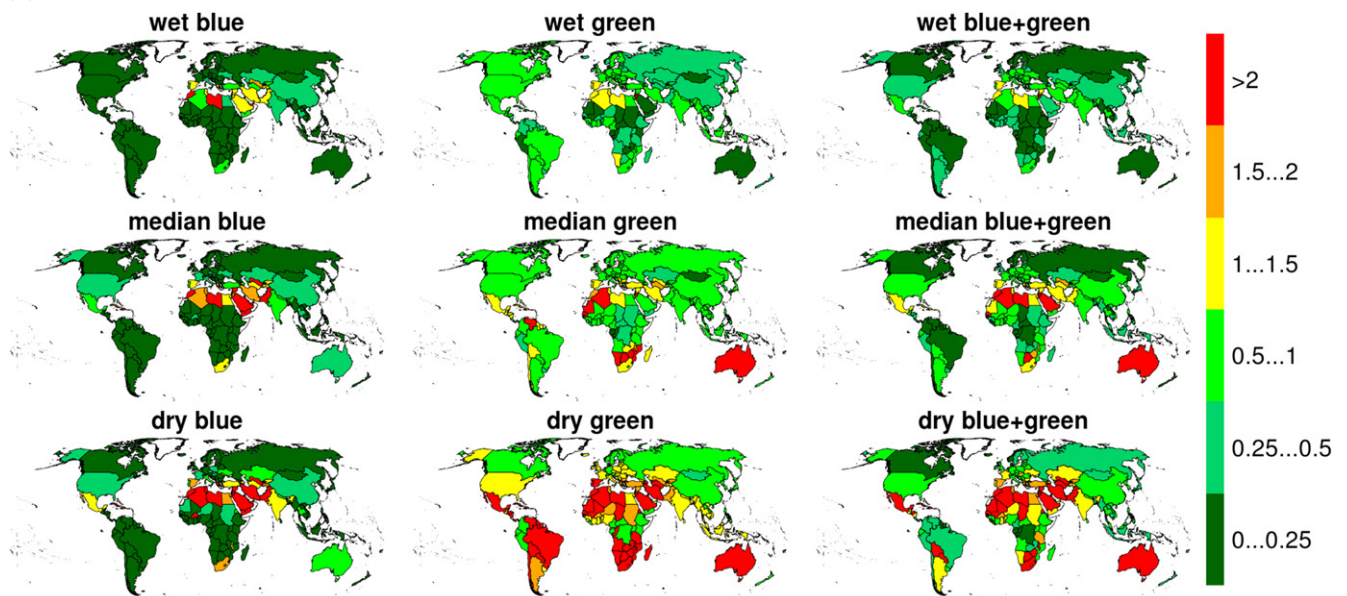
In terms of green water, many countries become water scarce in the future, especially for the dry case. This reflects the strong impact of increased radiation and temperature on evapotranspiration, which depletes soil moisture of transitional and dry regions (see also Seneviratne et al 2012, Orlowsky and Seneviratne 2012). The largest water scarcity increases are therefore diagnosed for the Mediterranean, North and South Africa, Central and South America as well as Central Asia. Since we equate present-day green water availability to present-day green  $WF_{area}$  (see section 3), the green water scarcity ratio basically reflects the changes in evapotranspiration (with a scarcity threshold given by the present-day  $WF_{area}$ ). The blue water scarcity ratio compares water availability and use more explicitly.

The maps of the scarcity of blue and green water together visually average the individual maps of green and blue water

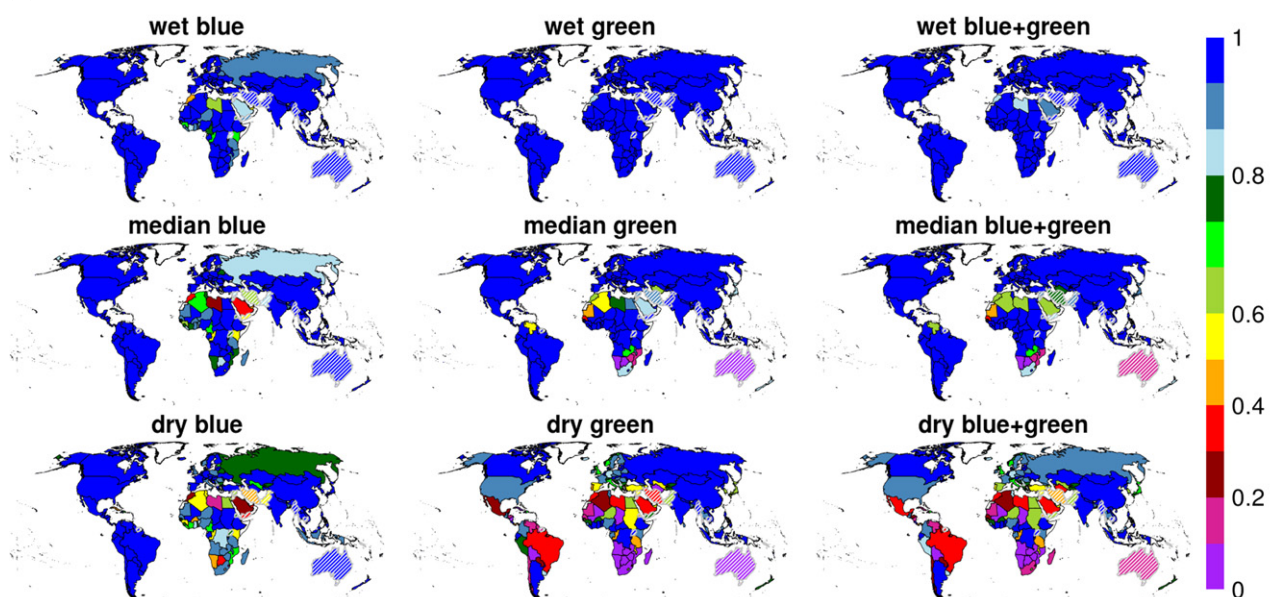


**Figure 2.** Scarcity ratio under present-day conditions for blue, green and blue+green water. Green colours indicate countries which are non-water scarce, yellow to red colours indicate increasing water scarcity.

(a) Scarcity ratio RCP8.5



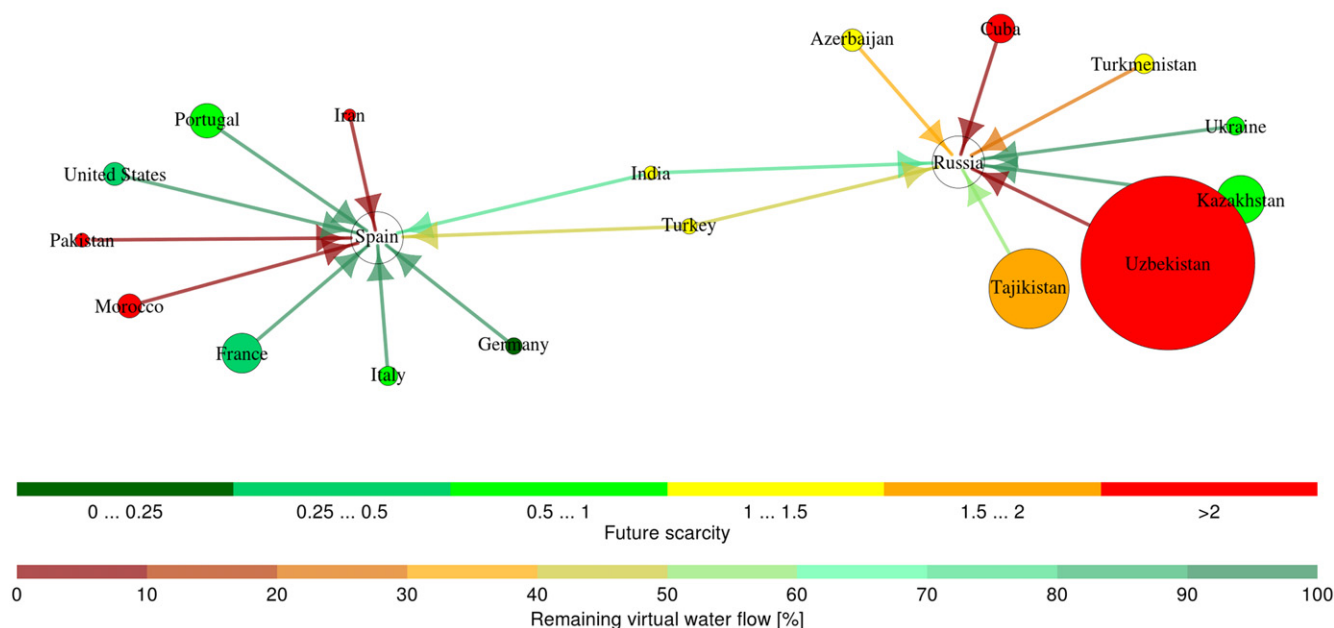
(b) Sustainability ratio RCP8.5



**Figure 3.** Scarcity and sustainability ratios for the future 2070–2099 period. (a) Scarcity ratios for blue, green and blue+green water. Green colours indicate countries which are non-water scarce, yellow to red colours indicate increasing water scarcity. (b) Sustainability ratios for blue, green and blue+green water. Blue colours indicate countries with sustainable water consumption, green to yellow to red colours indicate increasing degrees of unsustainability. Countries with relative adjustments of imports above 10% are highlighted with grey borders and white hashing (see section 2.1 and table 1 for a list of the countries). Both ratios are shown for the dry (10th percentile), median and wet (90th percentile) cases from the 35-member ensemble of RCP8.5 projections.



### Main blue flows to Russia and Spain, RCP8.5 dry case



**Figure 4.** Main flows (>200Mm<sup>3</sup> yr<sup>-1</sup>) of blue water into Spain and Russia for the future 2070–2099 period under the dry RCP8.5 case. The colours of each country show the per country blue water scarcity as in figure 3 (dry case) and the size of the circle indicates the relative magnitude of the present-day flows into Spain and Russia, respectively. The colours of the arrows indicate the degree of reduction of the virtual water flows under future water scarcity, green colours for no or little reduction and red colours for strong reductions.

scarcity. These findings are robust across the investigated spread of the ISI–MIP ensemble, with stronger changes for the dry end of the ensemble.

Regions of increased water scarcity correspond to regions where virtual water exports from domestic production  $Exp_{area}$  decrease (see figure S4 in the Supplementary Materials). The patterns of scarcity ratios are similar for the RCP2.6 GHG concentrations scenario, however, the changes into the future are generally weaker (see section S5 and figure S5 in the Supplementary Materials). Note that the spread of the ISI–MIP ensemble, that is the average difference between the wet and dry cases, is larger than the differences due to different GHG forcings for almost all countries (see section S6 and figure S7 in the Supplementary Materials). This aligns well with a recent study on drought indicators in GCM simulations (Orlowsky and Seneviratne 2013), which finds that GCM uncertainty is the dominant source of uncertainty in future drought projections, larger than uncertainties related to different GHG concentrations scenarios.

#### 4.2. Water constraints on national consumption

The lower half of figure 3 displays the sustainability ratios  $WF_{cons}(fut)/WF_{cons}(now)$ . It highlights countries where the total national consumption is not sustainable with respect to future patterns of reduced water availability, taking the effects of water scarcity on virtual water trades into account. As can be expected, many countries with increased scarcity ratios also display reduced sustainability ratios. Other countries which do not become water scarce themselves nevertheless show reduced sustainability ratios, which is a consequence of

reduced imports from trading partner countries which become water scarce (see e.g. the blue water sustainability of Russia). The consumption of other countries with increased scarcity ratio (e.g. blue water scarcity of Spain), on the other hand, does not decrease proportionally, if they import mainly from countries with enough water in the future.

The main blue water flows (>200Mm<sup>3</sup> yr<sup>-1</sup>) of Russia and Spain for the RCP8.5 dry case are illustrated in figure 4. Colours of the countries indicate their future scarcity ratios of the dry case, and their size indicates the relative magnitude of their present-day exports to Spain and Russia. The colours of the arrows indicate the degree of reduction of the virtual water flows. Spain imports mainly from ‘green’ countries with low scarcity ratios, which alleviates the effects of Spain’s high domestic scarcity. Russia, non-water scarce by itself, imports mainly from water scarce countries of Central Asia (of which Uzbekistan stands out), which affects Russia’s national consumption. Note, however, that the Central Asian countries are already blue-water scarce at present day. The effect on Russia reflects both an unsustainable present-day water management (in this case, excessive irrigation for cotton production) and the impact of reduced future availability in this region.

Table 3 summarizes these relations for all countries, combining blue and green water together for the dry, median and wet cases under the RCP8.5 scenario. It contains the cross tabulations of water scarce (scarcity ratio above 1) and non-water scarce countries versus ‘rather sustainable’ (sustainability ratio above 0.8) and ‘rather unsustainable’ countries. From wet to dry, we find a decrease of non-water scarce and ‘rather sustainable’ countries of (from 149 to 59) and an



**Table 3.** Cross-tabulations of the dry, median and wet cases under the RCP8.5 scenario, counting nations which are water scarce (scarcity ratio >1) or non-water scarce versus nations which are ‘rather sustainable’ (sustainability ratio >0.8) or ‘rather unsustainable’.

| Case   | Blue+Green Water     |                     |                    |
|--------|----------------------|---------------------|--------------------|
|        | Water scarcity       | Sustainability      |                    |
|        |                      | ‘sust.’, $\geq 0.8$ | ‘unsust.’, $< 0.8$ |
| Wet    | non-scarce, $\leq 1$ | 149                 | 0                  |
|        | scarce, $> 1$        | 23                  | 1                  |
| Median | non-scarce, $\leq 1$ | 118                 | 6                  |
|        | scarce, $> 1$        | 34                  | 15                 |
| Dry    | non-scarce, $\leq 1$ | 59                  | 25                 |
|        | scarce, $> 1$        | 25                  | 64                 |

increase of water scarce and ‘rather unsustainable’ countries (from 1 to 64). The mixed case of non-water scarce but ‘rather unsustainable’ conditions occurs in 25 countries in the dry case versus no countries in the wet case, again highlighting that it is essential to consider the virtual water trades when investigating the effects of reduced future water availability. The exact numbers depend strongly on the chosen thresholds, with for example higher sustainability thresholds leading to fewer water scarce but ‘rather sustainable’ countries. However, the overall findings regarding the three cases and the importance of virtual water flows are robust.

Note that we consider only the effects of reduced water availability. In a country with increased future water availability, reduced water imports can therefore be compensated from within-country resources. Since the way additional future water resources are used is a political and economical question, we cannot address it in our study which considers only the effect of climatological drivers on the national consumption and water trades. We therefore emphasize that a reduced sustainability ratio does not directly relate to a reduced consumption. It rather states the degree to which the present-day consumption of a country is affected by future water scarcity, either through within-country scarcity or scarcity elsewhere and associated reduced imports. Such reductions can potentially be compensated by increased water availability in other regions, however, even in this case the country needs to adapt its virtual water trades. The sustainability ratio thereby measures the adaptation need of a nation.

These patterns are similar under the RCP2.6 scenario, although the changes are overall weaker (see section S5 in the Supplementary Materials). As for the scarcity ratio, the ISI-MIP ensemble spread dominates over the differences due to the different RCP forcings for almost all countries (section S6).

## 5. Discussion and conclusion

This simple analysis shows that a reduced water availability due to climate change affects the water footprints within the area of the nations, most prominently for countries around the

Mediterranean. Given the reduced export capabilities of such countries, current trade patterns cannot be sustained into the future, which potentially causes changes to the virtual water consumption of importing nations, even if these do not become water scarce themselves. The patterns of affected water consumption are remarkably robust across the two analyzed GHG concentrations scenarios. In fact, the uncertainty in the patterns of future water availability due to the model-related spread in the ISI-MIP ensemble largely outweighs differences in GHG forcings.

We note several simplifications in our study.

- We do not consider the effects of increased future water availability, since these involve national and sub-national political and economic choices, which lie beyond the scope of our investigation.
- We have not considered future changes in water demand, thus underestimating future water scarcities, since demands are expected to increase due to population and economic growth and increasing demands for animal products and bioenergy (Ercin and Hoekstra 2014). Furthermore, water demands may increase or decrease as a result of climate change as well. Particularly in dry regions that will become drier, water demands will increase substantially. Climate change will thus impact water scarcity in those regions in two ways: not only through decreased water availability but also through increased water demand. This omission makes our results conservative.
- As in Hoekstra and Mekonnen (2012), we cannot trace the origin of a product (and the virtual water contained in it) further than one nation back, since any additional step would introduce circularity into our analysis.
- We make a conservative but strong assumption in that countries are expected to prioritize their internal and external consumption footprints over (re-)exports of virtual water. While an assessment of this assumption lies clearly beyond the scope of our study, one can imagine scenarios where countries choose a different priority order, for example if monetary gains from virtual water exports compensate for costs caused by a thereby further reduced internal water availability.
- We use long-term average changes of future water availability, neglecting changes in variability. While this simplification is a direct consequence of our static database on water footprints, it actually supports our first restriction of considering reduced water availability only, since increased water availability is often projected together with increased variability and extremes (heavy precipitation or floods, IPCC 2012) which are of little use to economic activity.

However, we argue that potential limitations due to these assumptions do not affect our main conclusions, (i), that a reduced water availability due to future climate change will reduce the water footprints within the area of some nations and, (ii), that their thereby reduced export capacity will affect the consumption in other countries, whether these become water scarce themselves or not. Even if in some regions water

availability increases, enabling an intensified production and/or exports (which we do not consider in our analysis), reorganization of the water trades and consumption becomes necessary to adapt to reduced trades and production in other regions. We thus identify the countries where climate change requires adaptation in terms of water consumption (see e.g. the situation in Russia). Our results highlight that the water availability within a country is not enough if one is interested in the virtual water consumption and we show that climate change will demand substantial changes to the water consumption and virtual water trade patterns as they exist today.

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