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# Virtual water flows, water footprint and water savings from the trade of crop and livestock products of Germany

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**Keywords**
blue water; crop products; European Union; Germany; global water savings; import-export; livestock products.

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## Abstract

Comprehensive assessment of the virtual water trade of Germany with the world is performed and the national water footprint through the trade of crop and livestock products from 1991 to 2016 is assessed. Virtual water flows based on 328 products with more than 200 countries indicate Germany as a net virtual water importer. Average virtual water import was 100.5 Bm$^3$/y, virtual water export was 60.2 Bm$^3$/y and net virtual water import was 40.3 Bm$^3$/y. Trade patterns of virtual water transfer differ for the various commodity types. Trade between Germany and the world implies a global water loss of 5.9 Bm$^3$/y. This study portrays that trade between countries is not only related to the economics but interlinked with the agricultural water use and management practices of the respective nations. Sustainable management of the resources will require a collective consideration of the agricultural, water and economic sectors while developing strategies.

## Introduction

The world population will reach 9.3 billion in 2050 and the world will need 70 to 100% more food to be produced to meet the demand (World Bank, 2007). So far, the area equipped for irrigation has increased from 184 million ha in 1970 to 324 million ha in 2012 (FAO, 2016). Global water withdrawals have also increased from <600 billion m$^3$/y (Bm$^3$/y) in 1900 to about 4000 Bm$^3$/y in 2010, of which 69% was for agricultural use (FAO, 2016). Freshwater accounts for 96% of the total global water withdrawals. As the finite freshwater resources are unevenly distributed around the world, several countries with scarce resources are not able to meet their domestic food demand locally and import from other countries (Oki and Kanae, 2004; Godfray *et al*., 2010; D'Odorico *et al*., 2014). Owing to the vast use of freshwater for agriculture and the trade of these agricultural products to other countries, the exporting countries are trading the water virtually embedded in the traded products. This water that is embodied in the production and trade of agricultural products is referred to as 'virtual water' (VW) (Allan, 1998). Water footprint (WF) introduced by Hoekstra (2003) is a closely linked concept to VW, an indicator of water use for all goods and services consumed by one individual or by the individuals of a country. It is a multi-dimensional indictor that specifies the volume of water consumed, water source, pollutant types, etc. and is composed of three components: green, blue and grey WF.

Since the introduction of the concept of VW and WF, research into this is booming in several parts of the world (Chen and Chen, 2013; Dalin and Conway, 2016; da Silva *et al*., 2016; Chouchane *et al*., 2018; SreeVidhya and Elango, 2019). Quantification of the VW flow (VWF) from one country to another is carried out at different spatial scales, for different products and using different approaches (top-down or bottom-up framework (Vanham and Bidoglio, 2013)). Eventually, some countries are given more importance and studied extensively (e.g. China, The United States of America (USA)) (Dang *et al*., 2015; Shao *et al*., 2017; Chini *et al*., 2017; Wu *et al*., 2019). Even though Germany is a key net VW importer through trade of agricultural products, VW studies on Germany are rarely reported.Nearly half of Germany's land area (47.7%) is used for agriculture. About 33 Bm$^3$ of freshwater is withdrawn per year, of which 14% is used for domestic and 83% for industrial uses (FAO, 2019). Agriculture uses only a small portion of the freshwater when compared with the abstraction for domestic and industrial purposes. Groundwater along with spring water and bank-filtered water form 70% of the source of drinking water (BMU, 2019). Germany ranks 9th in the world in the import of VW (1995–1999) (Hoekstra and Hung, 2002). The country tops the list of VW import (VWI) in the intra-EU trade and third in the VW export (VWE) (1993–2011) (Antonelli *et al*., 2017). Jiang and Marggraf (2015) studied the bilateral trade between Germany and China (2008–2011).

Hirschfeld (2015) reported Germany's annual VW trade (VWT) but did not provide details on the traded products or the trade countries. Another study concentrated on the VWT of Germany (2004–2006) with focus on selected countries and key products (Sonnenberg *et al*., 2009). Finogenova *et al*. (2019) investigated the water scarcity footprint of German agriculture imports for specific times (2000, 2005, 2010 and 2015).

To date, the VWT and the VWF of Germany through crop and animal products have been under-studied. The lacuna in the existing information makes it essential to document the VWT of Germany. Thus, this study presents an in-depth assessment of the VWT of Germany with the world from 1991 to 2016 through a detailed analysis of the traded products and distinguishing the VW components embedded in the products. The present study also quantifies the national WF and the water saved at the national and the global level because of the existing VWFs. This paper addresses the stress exerted on the freshwater resources, its role in the trade of agricultural products and provides a better understanding of the implications of VWT and the trade relations of Germany with other countries.

## Materials and methods

### Products traded

International trade pattern of agricultural products between Germany and partner countries are obtained from the database of the Food and Agriculture Organisation (FAO) of the United Nations (FAOSTAT, 2019). These data from 1991 to 2016 were collected for 328 products and were broadly classified into thirteen categories: cereals, cereal products (e.g. flour, bran, etc.), fruits, vegetables, live animals, animal-based products (e.g. meat, dairy, eggs, etc.), feed, nuts, oil, pulses, sugar, semi-luxury foods (e.g. spices, coffee, tea, etc.) and nonedible products (e.g. bran, cotton, wool, etc.). FAOSTAT (2019) reports agricultural products in tons (t) and live animals in 'heads'. This information was converted to 't' by multiplying the 'heads' with the average weight of the animal at the end of its lifetime (Mekonnen and Hoekstra, 2010b).

### Virtual water flows

The trade data (in tons/y) were converted to VWF (in $m^3$/y) by multiplying the quantity of products traded with the VW required to produce the product in the exporting country. The VW content (VWC) of the primary, secondary and tertiary products with the differentiation as green, blue and grey water is provided by Mekonnen and Hoekstra (2010a) and Mekonnen and Hoekstra (2010b). Green water refers to the volume of rainwater that is stored in the soil and used in the production process. This does not include the run-off or the recharge to groundwater. Fresh surface or groundwater used in the production is called blue water. Grey component denotes the volume of water that is polluted during the production process. It is quantified as the volume of water required to dilute the pollutants so that the ambient water quality standards are maintained (Hoekstra *et al*., 2011). Detailed methodology for the calculation of VWF is given in Hoekstra and Hung (2002). The Net VWI (NVWI) of a country is calculated as the difference between the VWI and VWE of the country. Positive NVWI values indicate that the country is a VW importer and negative values indicate that it is a VW exporter.

### Water savings and water losses

Water savings or losses of a nation were ascertained by calculating the difference between the volume of water required to produce a product in the country from where it is imported and the volume of water that would be required to produce the product domestically (Chapagain *et al*., 2006). VWT of a country can be in surplus or in deficit.

### National water footprint, water scarcity, water dependency and water self-sufficiency

VWT between countries and the current status of domestic water resources in the countries can beused to understand if the trade is sustainable or unsustainable. Depending on the NVWI and the water availability in the importing and exporting country, they can be classified into four types – mutually benefited, unilaterally benefited, supported and double-pressured countries (Zhang *et al*., 2016). This classification was adopted to understand the trade relations of Germany with other nations.

WF is calculated as a sum of the domestic water use and the NVWI (Hoekstra and Hung, 2002):

$$\text{Water footprint} = \text{WU} + \text{NVWI} \tag{1}$$

where WU is the total domestic water use ($m^3$/y), that is the water withdrawn for domestic, agricultural and industrial sectors (Gleick, 1993; FAO, 2016) and NVWI is the net virtual water import of the country ($m^3$/y). WF can either have a positive or a negative value similar to the NVWI. The WU should typically include the total green and blue water used. But, because of the difficulty in calculating the green water used by a country, this equation uses only the total blue water.

National water scarcity is calculated as a ratio of total water use to water availability (Hoekstra and Hung, 2002):

$$WS = \frac{WU}{WA} \times 100 \quad (2)$$

where WS is the national water scarcity (%), WU is the total domestic water use in the country ($m^3$/y) and WA is the national water availability ($m^3$/y).

Water dependency (WD) is a ratio of NVWI to total national water consumption:

$$WD = \frac{NVWI}{WU + NVWI} \times 100 \quad (3)$$

WD varies between 0 and 100%. If NVWI < 0, WD is 0. The above equation applies only if NVWI ≥ 0.

Water self-sufficiency (WSS) index is calculated as follows:

$$WSS = \frac{WU}{WU + NVWI} \times 100 \quad (4)$$

This equation can also be written as WSS = 1 − WD. The above equation applies if NVWI ≥ 0. If NVWI < 0, then WSS = 100.

# Results

## Overall virtual water trade

In total, 328 products traded by Germany were analysed in this study. Total products imported and exported by Germany were $1192.3 \times 10^6$ tons and $921.2 \times 10^6$ tons respectively. On average, Germany imports and exports $45.9 \times 10^6$ tons/y and $35.4 \times 10^6$ tons/y respectively. However, this does not represent the total volume of water used to produce the products. Figure 1a shows the changes in VWT through trade of crop and animal products from 1991 to 2016.

VWI was 81.7 $Bm^3$ in 1991 and increased to about 140 $Bm^3$ in 2016 with an average VWI of 100.5 $Bm^3$/y. Germany has imported 2613.6 $Bm^3$ of VW between 1991 and 2016. VWE was 39.1 $Bm^3$ in 1991 and raised to about 95.8 $Bm^3$ in 2016. Overall, 1564.7 $Bm^3$ of VW was exported during the study period. Average international VWE was 60.2 $Bm^3$/y. NVWI was 42.6 $Bm^3$/y in 1991 and 44.2 $Bm^3$/y in 2016 with an average of 40.3 $Bm^3$/y. In total NVWI was 1048.8 $Bm^3$ between 1991 and 2016. The NVWI was always positive through the study period showing that Germany consistently imports more VW than that is exported. The inter-annual changes (Fig. 1a) indicate a steady increase in the VWI and VWE. There is no distinct increase or decrease in the temporal variation of VWT.

Earlier studies reported that Germany ranked ninth in the list of countries that imported the largest VW (67.9 $Bm^3$) (Hoekstra and Hung, 2003). Chapagain and Hoekstra (2003) reported the VWI, VWE and NVWI of Germany as 37.3, 24.1 and 13.1 $Bm^3$/y respectively. Another study stated VWI as 64 $Bm^3$/y, VWE as 63 $Bm^3$/y and NVWI as 1 $Bm^3$/y (Zimmer and Renault, 2003). Hirschfeld (2015) reported Germany's annual VWI as 121 $Bm^3$/y and VWE as 71 $Bm^3$/y and NVWI as 50 $Bm^3$/y. Even though the volume of VW traded differs in these studies based on the number of products assessed, all the reported studies indicate that Germany is a VW importer.

## Green, blue and grey water

VWI of green, blue and grey water was 89.1, 5.1 and 6.4 $Bm^3$/y respectively. Green water was the most VW exported at an average of 50.9 $Bm^3$/y (Fig. 1b). Blue and grey water contribution to VWE was on average 2 and 7.3 $Bm^3$/y respectively. NVWI was positive for blue water (3.1 $Bm^3$/y) (Fig. 1c) and green water (38.2 $Bm^3$/y) (Fig. 1b) indicating that Germany imports more rainwater and freshwater resources than that is exported and it was negative for grey water (−1.0 $Bm^3$/y) (Fig. 1d). Hirschfeld (2015) reported the variation in the type of VW traded as 6 $Bm^3$/y of blue water, 57 $Bm^3$/y of green water and 58 $Bm^3$/y of grey water through VWI and 2 $Bm^3$/y of blue, 28 $Bm^3$/y of green and 41 $Bm^3$/y of grey water as VWE.

In case of the green water, VWI had increased from 72 to 123.9 $Bm^3$/y during the initial and final period of study (Fig. 1b). This is nearly a twofold increase in green VWI. The increase in VWI component was more prominent in grey water which increased twofold from 4.9 $Bm^3$ in 1991 to 10 $Bm^3$ in 2016 (Fig. 1d). Blue water VWI although shows an increase, it is more gradual, that is 4.6 and 6.1 $Bm^3$ in 1991 and 2016 (Fig. 1c) respectively. It should be noted that there is an obvious increase in the green VWE, that is from 32.4 $Bm^3$/y in 1991 to 81.3 in 2016, more than a twofold increase (Fig. 1b). Grey VWE had increased twofold, that is from 5.0 $Bm^3$ in 1991 to 11.1 $Bm^3$ in 2016 (Fig. 1d). In contrast, blue VWE shows the least increase from 1.7 $Bm^3$/y in 1991 to 2.7 $Bm^3$/y in 2016 (Fig. 1c).

The main variation in the VW components depends on the agricultural practice and technological advances available in the land of production (Wichelns, 2001; Goswami and Nishad, 2015). The results state that rain-fed agriculture (i.e. with green water) dominates the agricultural

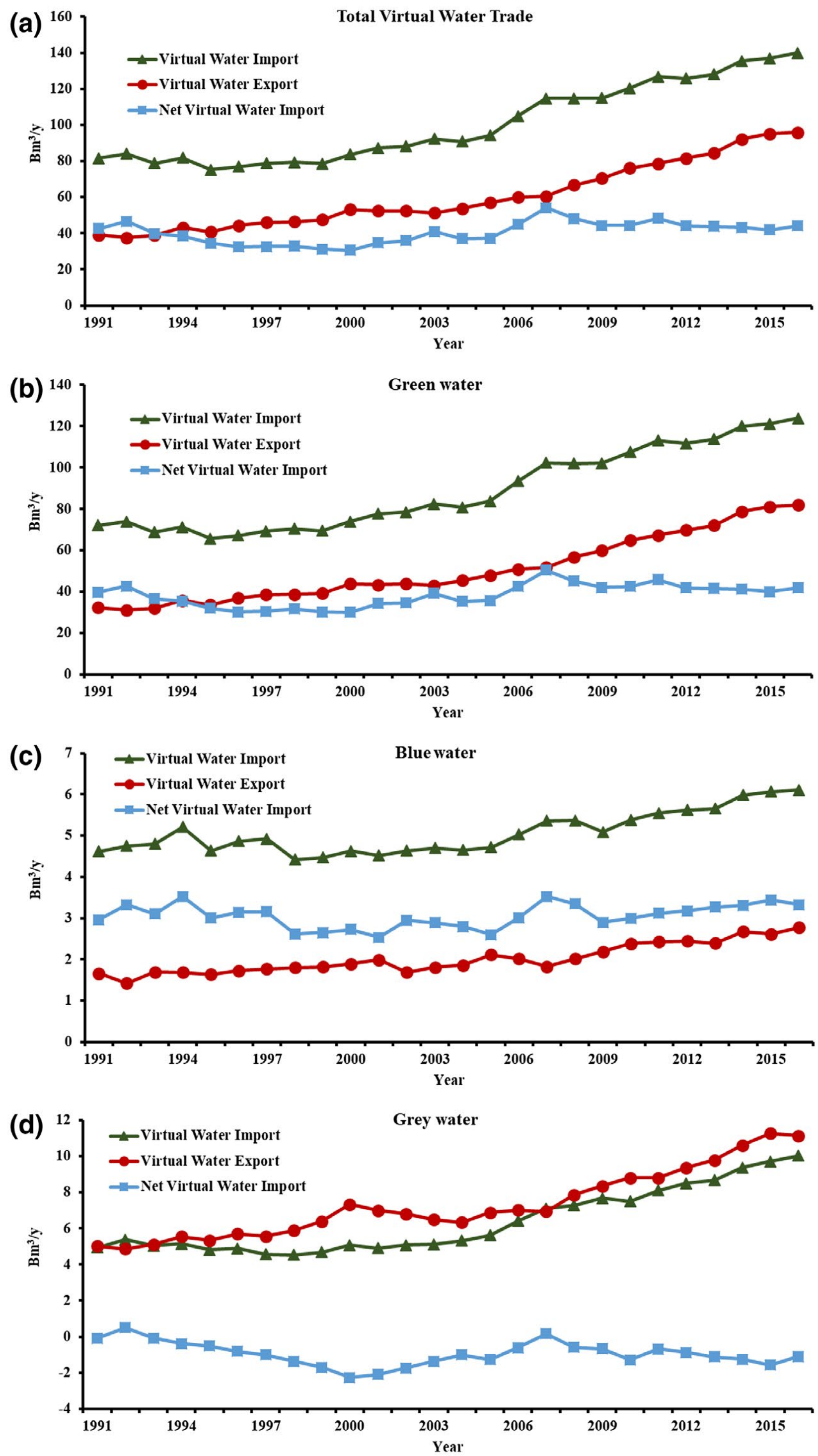


**Fig. 1.** (a) Virtual water trade of Germany from 1991 to 2016. Virtual water trade based on (b) green, (c) blue and (d) grey water.

production method in both Germany and the countries exporting to Germany. The freshwater resources (i.e. blue water representing surface water and groundwater) are the least used water type for crop and livestock production. The variation in the irrigation practices can be viewed clearly from the higher grey VWC (this study, Hirschfeld, 2015; Jiang and Marggraf, 2015) which indicates a larger volume of water is required for diluting the pollution from agricultural practices in Germany compared to the other countries from where Germany imports.

## Analysis of food categories

A study by Hoekstra and Hung (2003) calculated the VWF of Germany from crop products (i.e. not including live animals or animal-based products) as 23.3 $Bm^3/y$ for VWI, 9.7 $Bm^3/y$ for VWE and 13.6 $Bm^3/y$ as NVWI. Chapagain and Hoekstra (2003) reported the NVWI of Germany from trade of livestock and livestock products as –0.5 $Bm^3/y$. Variation over the study period showed that crop products are consistently traded in larger quantities than the livestock products. Nonedible products (also referred as industrial products) usually make a lower contribution to VWF than the agricultural products, which has also been observed by others (Jiang and Marggraf, 2015). To identify the variation in the VW contribution from crop and livestock production, the food categories were grouped into crop (cereals, cereal products, nuts, oil, pulses, sugar, fruits, vegetables, semi-luxury foods and feed), livestock (live animals and animal-based products) and industrial products (nonedible products).

Crop products dominate the VWI by 77% (77.7 $Bm^3/y$) followed by livestock products (15.8 $Bm^3/y$). Crop and livestock products contributed to 70 and 27% of the VWE respectively. NVWI contribution by crop, livestock and industrial products were 35.4, –0.5 and 5.4 $Bm^3/y$ respectively. Cereals, cereal products, sugar and animal-based products are exported more than the imports, thus having a negative NVWI. The other food categories portray a positive NVWI. A detailed list of the volume of VW contributed by the different food categories under green, blue and grey water are given in Table 1. Variation in the VWT of the various food categories during the study period is shown in Fig. S1 (Supporting Information).

## Analysis of individual food products

The top-10 products that contributed to the largest VWI and VWE are given in Table S1. This list is based on the total VWC and is not classified based on the largest green, blue and grey water contribution. These top-10 products contribute to 51% of VWI and 50% of VWE. It is noticeable that most of the top-10 items are from crop products and livestock contributes to a lesser extent.

The top-10 products contribute to 56% of green water, 44% of blue water and 46% of grey water imports. Coffee, various oilseeds and nuts play a key role in the VWI of Germany. Top-10 products based on green water content are the same as the total VWI (Table S1). Crucial products imported by Germany that depend on freshwater resources (blue water) are cotton lint, pistachios, rice, shelled almonds, glucose and dextrose, soybeans, refined sugar, pig meat, live pigs and castor bean oil. Most of the grey water is contributed by coffee-green, rapeseed, wheat, shelled almonds, feed and meal, live pigs, pig meat, maize, palm oil and tobacco. Similar products were reported as crucial imports by Sonnenberg *et al*. (2009).

VWE is dominated by 51% for green water, 61% for blue water and 50% for grey water from the top-10 products. Top-10 VWE products based on green water content are the same as the total VWE (Table S1). Largest blue water exported were through refined sugar, pistachios, chocolate products, sugar confectionary, glucose and dextrose, orange juice, pig meat, pork, cheese from whole cow milk and cotton lint. Key grey water-contributing products were wheat, barley, soybean cake, rapeseed oil, soybean oil, pig meat, pork, sunflower oil, meat and cheese from whole cow milk.

## Virtual water trade with various continents

Most of Germany's VWF were within Europe (Table S2). About 55% of VWI and 77% of VWE are with European countries. Following Europe, Asia and South America each contributed individually for 16% of VWI. Germany exported 13% of its VW to Asia. Lowest VWE was to South America and Oceania (each 1%). Among the NVWI, most VW is saved with South America (38%), followed by Asia (20%) and Europe (19%). VWI from the European nations was 54% of green, 58% of blue and 67% of grey water. Asian countries import 23% blue, 16% green and 11% grey VW. VW exported from Germany to European countries contained 78% blue, 78% green and 74% grey water. Asian countries import 15% blue, 12% green and 16% grey water from Germany. NVWI was positive for green and blue water with all the continents. Most green water trade through NVWI was with South America (39%), Africa (20%) and Asia (20%). NVWI for blue water was the highest with Europe (44%) and Asia (28%). Grey water net import was positive with North America, South America and Oceania indicating more import than export. However, net grey water import was negative with Europe, Asia and Africa showing that the import from the countries in these continents exceeds the exports from Germany.

## Virtual water trade with specific countries

VWF between Germany and other countries are classified into three types. Initially, all the countries were assessed together. Later, as more than 50% of Germany's trade is with countries within Europe, a differentiation of the countries into EU and non-EU nations were considered. EU countries contain 32 nations including the EU member States (EU28) and the countries that are part of the

**Table 1** Total virtual water trade from 1991-2016 based on various food categories

| Food category | Virtual water import ($Bm^3$) | | | | Virtual water export ($Bm^3$) | | | | Net virtual water import ($Bm^3$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Green water | Blue water | Grey water | Total | Green water | Blue water | Grey water | Total | Green water | Blue water | Grey water | Total |
| Cereals | 101.56 | 9.22 | 20.85 | 131.63 | 142.54 | 0.89 | 47.46 | 190.89 | -40.97 | 8.32 | -26.6 | -59.25 |
| Cereal products | 32.98 | 0.71 | 4.08 | 37.77 | 46.42 | 0.67 | 9.72 | 56.81 | -13.43 | 0.04 | -5.63 | -19.02 |
| Nuts | 50.93 | 21.43 | 12.52 | 84.88 | 10.47 | 4.59 | 1.48 | 16.54 | 40.46 | 16.84 | 11.04 | 68.34 |
| Oil | 675.86 | 14.74 | 33.08 | 723.68 | 204.73 | 0.81 | 43.91 | 249.45 | 471.13 | 13.93 | -10.82 | 474.24 |
| Pulses | 1.85 | 0.09 | 1.16 | 3.1 | 0.33 | 0.03 | 0.08 | 0.44 | 1.51 | 0.06 | 1.08 | 2.65 |
| Sugar | 34.91 | 14.22 | 3.42 | 52.55 | 49.23 | 20.02 | 4.76 | 74.01 | -14.31 | -5.79 | -1.34 | -21.44 |
| Fruits | 106.9 | 21.42 | 13.92 | 142.24 | 30.57 | 3.71 | 2.36 | 36.64 | 76.32 | 17.7 | 11.55 | 105.57 |
| Vegetables | 22.98 | 4.83 | 6.01 | 33.82 | 7.59 | 0.82 | 2.15 | 10.56 | 15.39 | 4.01 | 3.86 | 23.26 |
| Semi-luxury foods | 746.22 | 7.29 | 19.27 | 772.78 | 432.71 | 4.72 | 8.65 | 446.08 | 313.51 | 2.56 | 10.61 | 326.68 |
| Feed | 30.4 | 0.79 | 6.75 | 37.94 | 13.76 | 0 | 4.23 | 17.99 | 16.64 | 0.79 | 2.51 | 19.94 |
| Live animals | 68.5 | 3.75 | 8 | 80.25 | 43.62 | 1.28 | 7.74 | 52.64 | 24.87 | 2.46 | 0.26 | 27.59 |
| Animal-based products | 288.04 | 16.37 | 25.89 | 330.3 | 304.09 | 11.98 | 54.66 | 370.73 | -16.05 | 4.38 | -28.77 | -40.44 |
| Nonedible products | 155.42 | 16.81 | 10.39 | 182.62 | 36.23 | 2.77 | 2.9 | 41.9 | 119.18 | 14.04 | 7.49 | 140.71 |
| Total | 2316.55 | 131.67 | 165.34 | 2613.56 | 1322.29 | 52.29 | 190.1 | 1564.68 | 994.25 | 79.34 | -24.76 | 1048.83 |

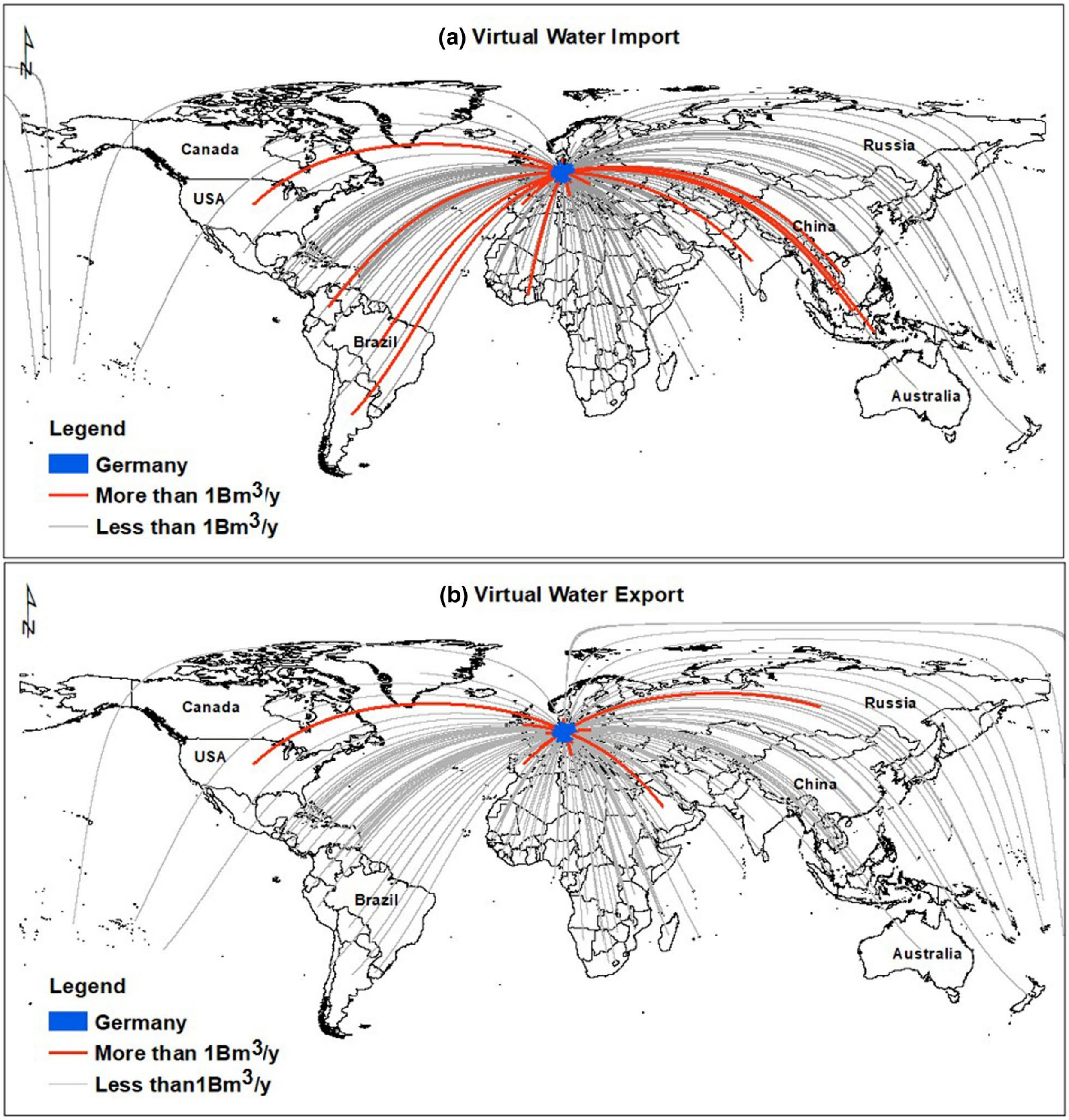


**Fig. 2.** Virtual water flows of Germany.

European Free Trade Agreement (EFTA) (Antonelli *et al*., 2017).

Top-10 nations contributing to the VWI are the Netherlands, Brazil, France, Indonesia, the USA, Belgium, Italy, Poland, Denmark and Malaysia. 61% of the VWI is from these ten countries and Germany imports more than 1 $Bm^3/y$ from 21 countries (Fig. 2a). Six of the ten countries are part of the EU. Most green water import is from the same ten countries that contribute overall to the VWI (Table S3). The Netherlands exports the most VW in the form of green, blue and grey water to Germany (Table S3). Detailed information on the list of the top-10 countries and the volume of VW imported are given in Table S3.

Germany exports the most VW to the following ten countries: The Netherlands, France, Italy, Poland, Austria, the United Kingdom (UK), Denmark, Belgium, Russia and Czech Republic (Table S3). These ten countries contribute to 66% of the total VWE and Germany trades >1 $Bm^3/y$

with 14 countries (Fig. 2b). VWE through green water follows the same trend as that of total VWE (Table S3). Highest blue and grey water export is also largely to EU nations (Table S3). From the bilateral trade analysis between Germany and China, Jiang and Marggraf (2015) calculated the VWE from Germany to be 192 million $m^3$/y ($Mm^3$/y) and VWI from China as 801 $Mm^3$/y and indicated China as a major VWT partner of Germany. In the present study, the VWE to China was 401 $Mm^3$/y and VWI from China was 579 $Mm^3$/y and China was not among the top-10 countries that contributed significantly to the VWT of Germany. However, both studies indicate that Germany is a net importer of VW from China.

List of positive NVWI for the top-10 countries are the Netherlands, Brazil, Indonesia, the USA, Malaysia, Ivory Coast, Colombia, France, Belgium and Argentina. The Netherlands tops the list for largest VWI from Germany in the form of green and blue water and the USA tops the list for the largest grey water imported (Table S3). Negative NVWI, that is Germany exports more VW than that is imported to the following top-10 nations: Austria, Italy, the UK, Russia, Poland, Saudi Arabia, Sweden, Algeria, Slovakia and Greece. Distinguishing the VWT with EU and non-EU nations, it is interesting to note that most of the VWE is to EU nations (79%), but VWI does not vary widely with EU (55%) and non-EU nations (45%) (Table 2). It is also noted that more freshwater resources are imported from EU nations. A detailed list of the EU and non-EU countries and the volume of VW traded with Germany in the form of green, blue and grey water is given in Tables S4 and S5.

## Water savings and water loss

Water savings is one of the major positive effects because of VWT between nations (Chapagain *et al*., 2006). The volume of water saved or lost by Germany through VWT with the world is quantified by calculating the difference between the volume of water required to produce a desired product from where it is imported and the volume of water required to produce the same product within Germany. This analysis will identify if Germany is contributing to global water savings by importing the product and not producing them domestically or if it is contributing to global water losses through the trade.

About 94.6 $Bm^3$/y of VW is used to produce the products in Germany for which 100.5 $Bm^3$/y of VW is required in other countries (Table 3). Overall, trade between Germany and the world leads to global water loss of –5.9 $Bm^3$/y. Other countries use 89.1 $Bm^3$/y of green water and 6.4 $Bm^3$/y of grey water whereas Germany would use 81.5 $Bm^3$/y of green water and 10.2 $Bm^3$/y of grey water (Table 3). Germany would have used lesser freshwater resources, that is about 2.9 $Bm^3$/y while 5.1 $Bm^3$/y is used by other countries. Global water savings is chiefly through the trade from oil, pulses and semi-luxury foods, while global water losses are because of trade from other food categories. In terms of blue water, except for pulses, all other food categories lead to global water loss (Table 3). Largest blue water loss is through fruits > oil > nuts > animal-based products > sugar > cereals > nonedible products. Top-10 countries where water is saved are with Vietnam, Ivory Coast, Brazil, Turkey, Colombia, Ethiopia, Peru, Greece, Costa Rica and Argentina. Water is lost with the following top-10 countries: France, Poland, Indonesia, Belgium, Czech Republic, Netherlands, Hungary, Spain, Malaysia and Thailand.

## Calculation of trade partnership and various indices

Based on the NVWI and the abundance of water resources in a country, Zhang *et al*. (2016) classified trade partnership into four types – mutually beneficial, partially beneficial, unsustainable and pressured. A country is considered to possess abundant water resources if the renewable internal

**Table 2** Virtual water trade of Germany with EU and non-EU countries

| Virtual water trade | Virtual water type | With EU nations ($Bm^3$/y) | With non-EU nations ($Bm^3$/y) | Total ($Bm^3$/y) |
|---|---|---|---|---|
| Import | Green | 48.10 | 40.99 | 89.09 |
| | Blue | 2.95 | 2.10 | 5.05 |
| | Grey | 4.27 | 2.09 | 6.36 |
| | Total | 55.32 | 45.18 | 100.50 |
| Export | Green | 40.52 | 10.33 | 50.85 |
| | Blue | 1.57 | 0.43 | 2.00 |
| | Grey | 5.56 | 1.74 | 7.30 |
| | Total | 47.65 | 12.50 | 60.15 |
| Net virtual water import | Green | 7.58 | 30.65 | 38.23 |
| | Blue | 1.38 | 1.67 | 3.05 |
| | Grey | –1.29 | 0.34 | –0.95 |
| | Total | 7.67 | 32.66 | 40.33 |

**Table 3** Water savings and loss from trade of food products under various food categories

| Food category | Virtual water content of food from partner countries (Mm$^3$/y) | | | | Virtual water content of food if produced in Germany (Mm$^3$/y) | | | | Water savings/lost (Mm$^3$/y) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Green | Blue | Grey | Total | Green | Blue | Grey | Total | Green | Blue | Grey | Total |
| Cereals | 3906 | 354 | 802 | 5062 | 3335 | 133 | 936 | 4404 | –570 | –221 | 134 | –657 |
| Cereal products | 1268 | 27 | 157 | 1452 | 1092 | 16 | 220 | 1328 | –176 | –10 | 63 | –123 |
| Nuts | 1959 | 824 | 481 | 3264 | 2155 | 501 | 336 | 2992 | 196 | –323 | –145 | –272 |
| Oil | 25 994 | 567 | 1272 | 27 833 | 23 753 | 212 | 4606 | 28 571 | –2241 | –354 | 3333 | 738 |
| Pulses | 71 | 3 | 44 | 118 | 120 | 11 | 30 | 161 | 49 | 7 | –14 | 42 |
| Sugar | 1342 | 547 | 131 | 2020 | 866 | 308 | 86 | 1260 | –476 | –239 | –45 | –760 |
| Fruits | 4111 | 823 | 535 | 5469 | 3976 | 410 | 499 | 4885 | –134 | –412 | –35 | –581 |
| Vegetables | 884 | 186 | 231 | 1301 | 936 | 114 | 223 | 1273 | 52 | –71 | –7 | –26 |
| Semi-luxury foods | 28 701 | 280 | 741 | 29 722 | 29 307 | 257 | 711 | 30 275 | 606 | –22 | –29 | 555 |
| Feed | 1169 | 30 | 259 | 1458 | 706 | 0 | 217 | 923 | –462 | –30 | –42 | –534 |
| Live animals | 2634 | 144 | 307 | 3085 | 2294 | 118 | 497 | 2909 | –340 | –25 | 189 | –176 |
| Animal-based products | 11 078 | 629 | 995 | 12 702 | 8619 | 349 | 1572 | 10 540 | –2458 | –279 | 576 | –2161 |
| Nonedible products | 5977 | 646 | 399 | 7022 | 4343 | 449 | 264 | 5056 | –1634 | –197 | –135 | –1966 |
| Total | 89 094 | 5060 | 6354 | 100 508 | 81 502 | 2878 | 10 197 | 94 577 | –7588 | –2176 | 3843 | –5921 |

**Table 4** Trade partnership based on the net virtual water import and total internal renewable freshwater resources per capita

| Trade type | Net virtual water import | Water availability | Suggested approach (based on Zhang ***et al***., 2016) | Countries (as examples) |
|---|---|---|---|---|
| Mutually beneficial | Positive | Water abundant (the total internal renewable freshwater resources >1000 m$^3$/capita/y) | Import from partner countries can be continued | Brazil, France, Indonesia, USA |
| Partially beneficial | Negative | | Importing from countries under this category is not harmful. However, it is beneficial to reduce the net virtual water import by producing part of the requirement domestically or by importing from countries that use less virtual water to produce the product | Austria, UK, Poland, Japan |
| Unsustainable | Negative | Water scarce (the total internal renewable freshwater resources <1000 m$^3$/capita/y) | Desirable to produce the food product domestically | Saudi Arabia, South Africa, Bangladesh, Jordon |
| Pressured | Positive | | Substitute trade partners which uses less virtual water for the desired product | Pakistan, Hungary, Zimbabwe |

freshwater resources per capita of the country are larger than those of the world. More detailed information on the classification of trade partners is given in Zhang *et al*. (2017), Zhang *et al*. (2016), Brindha (2019) and Brindha (2017). The countries were distinguished based on this classification and the suggested method to improve the trade at the same time sustainably using the national water resources is given in Table 4.

Total annual freshwater withdrawals of Germany were available for the years 1991 (46.3 Bm$^3$), 1995 (45.2 Bm$^3$), 2001 (39.11 Bm$^3$), 2007 (32.3 Bm$^3$) and 2010 (33 Bm$^3$) (FAO 2019). Based on the NVWI calculated for the study period (1991–2016), the WF of Germany calculated for the above-mentioned years varies from 74 to 88.9 Bm$^3$. Usually for WF calculation, the total domestic water use will include the groundwater and surface water (blue water) and the rainwater (green water), but because the green water data are not easily calculated, the information only on the blue water is taken into consideration. This is a limitation of this calculation (Hoekstra and Hung, 2003). Sonnenberg *et al*. (2009) reported very high WF of 159.9 Bm$^3$/y which included 117.6 Bm$^3$/y of WF from agricultural products and 36.4 Bm$^3$/y of WF from industrial products.

Considering the total population of Germany, WF per capita in Germany has reduced from 1110 m$^3$/y per capita in 1991 to 945 m$^3$/y per capita in 2010, which is greater than the WF for Germany reported by Hoekstra and Hung (2003) (742 m$^3$/y per capita). BMU (2019) has reported that the consumption of drinking water in Germany showed a decline in the past 15 years, that is from 144 litres per capita per day in 1991 to between 120 and 123 litres per capita per day currently. But this represents only a small portion of water consumption compared to the VWI. The global WF is 7451 $Bm^3$/y and per capita WF is 1240 $m^3$/y (Hoekstra and Chapagain, 2007). The WF of Germany is lower than the values estimated in this study. Gawel and Bernsen (2011) reported the WF per capita as 1545 $m^3$/y and the total WF of Germany as 126.95 $Bm^3$/y.

Water availability in Germany is estimated at 188 $Bm^3$ (Hirschfeld *et al*., 2014). Based on this, the WS in Germany for 2014 was calculated as 18%, WD as 57% and WSS is 43%. The WS has decreased from 28% since the study by Hoekstra and Hung (2003) (held for the period 1995–1999) while the WD has increased more than two times (22% during 1995–1999). Chapagain and Hoekstra (2008) considered the total renewable water resources of Germany as 154 $Bm^3$/y and reported Germany to be 82% water scarce and 53% water dependent (during 1997–2001). The WSS was at 78% during 1995–1999 (Hoekstra and Hung, 2003) and has reduced to 47% in 1997–2001 (Chapagain and Hoekstra, 2008) and 43% in 2014 (this study).

## Discussion

Sustainable use and management of water resources have been typically considered as a matter of local concern. But recently, water withdrawal, consumption and depletion is viewed in a global context and management plans are taken with an international perspective (Hoekstra and Mekonnen, 2012; Vörösmarty *et al*., 2015). VW studies contribute to applying the global dimension to the water withdrawals and consumption pattern. It is obvious from this study that the domestic consumption of food in Germany is associated with water consumption globally. Germany is both water and land-rich country and the food security of Germany at the moment is not threatened. It is also self-sufficient in terms of the per capita food production to a balanced diet of 2700 kcal/capita/day (D'Odorico *et al*., 2014). Yet, Germany depends significantly on international trade relations for its domestic requirements, especially for semi-luxury foods and livestock. The total global VWE is calculated as 1625 $Bm^3$/y (Chapagain and Hoekstra, 2008). Based on this, the VWE from Germany contributes to 27% of the global exports and VWE from other countries contributes to 16% of VWI of Germany.

Globally, more preference is given to the use of green water for production than the limited blue water resources in order to reduce negative ecological impacts. Import and export of VW in the form of green water is apparently larger for Germany than blue and grey water. However, there is increasing stress on the water resources from groundwater withdrawals to meet the water and food requirements of the increasing population. The rate of abstraction has outrun the rate of replenishment in many nations with agriculture-based economy. The total internal renewable freshwater resource of Germany is 1321 $m^3$/cap/y (FAO, 2019) and Germany is considered as a water-stressed nation. Apart from the issues faced because of local water use, climate change will also affect the availability of green and blue water spatially, quantitatively and qualitatively (Harrison *et al*., 2013; Rodrigues *et al*., 2014; Lee and Bae, 2015). Even countries with rich water resources such as Germany are vulnerable to the negative effects of climate change in the form of droughts and floods. If Germany reduces the import of products consuming more blue water, this will reduce the burden on the importing country's freshwater resources. This can be achieved by identifying countries that use more green water and less blue water to produce the product or a country that uses better agricultural practices and uses overall less water for production. But this is a complex assessment and cannot be performed just by considering the green and blue VWC. It depends on the land and water availability, trade and policies, labour, technology used, etc. in the exporting country.

It is established that the trade of agricultural products influences water use in a country and hence the agricultural and trade policies should include the water aspect when framing strategies. Nevertheless, it is not easy to directly connect the VWF with the social and environmental consequences or help to frame policy measures (Hirschfeld *et al*., 2014; Marta and Martina, 2014). It is also not explicitly possible to point out how the ecosystem in the exporting country is affected. But it can help to evaluate the interlinking effects of agriculture, water resources and economics through trade in a cumulative way. VW studies may not help to alleviate water stress or save water, but they act as indicators to allow us to quantify the volume of water that is used.

This study, although based on a national point of view, shows that there will be local and global benefits if the following options are adopted by Germany:

**(1)** *Reduce food dependency*: Germany may consider improving its food security by increasing the food production for essential crop and livestock products and reduce import from other countries. This is much more complex and depends on soil type, rainfall, land and water availability, etc. and cannot just be based only on the VWC of crops and livestock. If Germany reduces the import from other countries, the revenue of the exporting countries and the international trade will be affected. Thus, this option is more beneficial at the local level than at the global scale.

**(2)** *Efficient irrigation technologies*: From the grey water composition of the products produced in Germany, it is clear that new agricultural technologies should be adopted by Germany to reduce the pollution of water resources. More efficient methods of water use in agriculture can reduce the VWC (especially blue and grey water) of crops and livestock.

**(3)** *Trade diversification*: Germany's trade should take into consideration the VWF. This is not a simple process and water alone cannot be used to determine the trade or develop policies. Information on water has to be used in combination with foreign relations and economic policies. This can assist in reducing the negative impacts on the ecosystem of the countries that consume high VW to provide water-intensive products imported by Germany.

**(4)** *Change in food consumption patterns*: Water use and food requirements will increase with the growing population in the near future. This is also subject to change with the consumption patterns. Today, shifting meat-based diet has increased the total water consumption for livestock production. Hence, it will be beneficial to link the VWT with food consumption and diet patterns of the country, especially considering the fact that Germany consumes a large number of water-intensive products such as coffee, cocoa, chocolates and livestock. By making modifications to the food consumption patterns, water consumption for these semi-luxury foods and livestock will be reduced.

**(5)** *Reducing food waste:* Nearly 55 kg of food/capita/year is wasted in Germany. This is not just a serious ethical and economical issue, but also a waste of land and water resources. Although it is difficult to eradicate food waste completely, reducing it will not only save these natural resources, but also help to redistribute food, and indirectly water to other regions where needed.

## Conclusion

**(1)** Food production is dependent on availability and access to land and water. The finite global freshwater resources are subject to increasing pressure because of population growth, economic growth and climate change.

**(2)** Countries with limited freshwater resources available for agriculture cannot meet the demand through domestic production and have to rely on imports from other countries. In comparison with the number of VW studies available for other European countries, the number of studies on VW of Germany is relatively less.

**(3)** The present study attempts to understand water consumption and water stress on the freshwater resources of Germany through analysis of the VWF and the national WF. Germany is highly dependent on the water resources of importing countries for its food requirements. The VWI of Germany was 100.5 $Bm^3$/y, VWE was 60.2 $Bm^3$/y and NVWI was 40.3 $Bm^3$/y.

**(4)** Trade between Germany and other countries indicate global water loss. The evaluation of the international trade of agricultural products is complex and is dependent on a number of factors such as land and water availability, advances in agriculture technology, manpower, etc.

**(5)** Although it is widely argued that VW studies cannot be used to frame policy measures or changing the trade partnerships will not save the water in the water-scarce countries, it can create awareness about water consumption and identify any negative impacts.

**(6)** This study indicates that VWT analysis can provide useful insights into the agriculture and water resources of a nation that serve as supporting information while amending trade, economic and foreign policies.

## Conflict of interest

None

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## Data availability statement

Datasets used in this study are publicly available online from the references quoted under materials and methods.



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