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Assessment of wheat's water footprint and virtual water trade: a case study for Turkey

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Abstract

Background: Many countries are experiencing significant water scarcity and related problems due to limited availability, uneven distribution of water resources and high demand. Therefore, increasing water use efficiency and better management of existing resources have become substantially important. The agricultural sector is responsible for around 80% of global freshwater withdrawal. Wheat is one of the most important crops having large volumes of virtual water (VW) which is defined as the hidden water embedded in the products.

Methods: Water footprint (WF) is an indicator showing the total volume of freshwater consumption of a product or process. Blue water concept is defined as the amount of exploited surface and groundwater resources. Green water represents the total volume of rainwater allocated by the product. WF methodology brings a new approach to inter-regional water use and management by quantifying the amount of direct and indirect water use and tracing the hidden links between production, consumption and trade. The main objective of this study is to analyze Turkey's national blue and green WF of wheat production, consumption and virtual water trade between 2008 and 2019. Detailed province-based quantification of wheat's water exploitation is provided using spatial interpolation method.

Results: Total consumptive WF of wheat production and consumption of Turkey is calculated as 39.3 and 48.1 Gm^3/year, respectively. The average blue and green VW contents of wheat production through Turkey are assessed to be 1161 and 748 m^3/ton, respectively. The water footprint parameters of each province are calculated and discussed using climatic and agricultural data. VW transfer of Turkey's international wheat trade is also analyzed. Total national water saving is calculated as 7.8 Gm^3/year which is mostly imported from Russia. Global VW deficit due to international wheat trade is calculated to be 1.76 Gm^3/year.

Conclusion: Despite its high contribution to global wheat production, increasing population and strong wheat-based diet, quantitative, comparative and up-to-date analyses of the blue and green WF and the VW transfer of wheat production in Turkey are not available. This study contributes to the national and international water management and planning studies to increase the water allocation efficiency of agricultural products.

Keywords: Evapotranspiration, Spatial interpolation, Agriculture, Management, Sustainability, Transfer

Introduction

Wheat in the world and Turkey

Wheat (*Triticum aestivum*) is one of the most cultivated cereal grains in the world (Mekonnen and Hoekstra 2010a), exceeding 200 million hectares of land area and providing around one-fifth of the total calorific input of world's population (Thapa et al. 2019). According to some researches, the Southeastern Anatolia is the homeland of domestic wheat (Dubcovsky and Dvorak 2007; Mekonnen and Hoekstra 2010a). World's wheat demand grows by approximately 2% annually (Keser et al. 2017). Around 20% of global wheat production is provided by irrigation. Despite its adaptation to water-stressed regions, the availability of groundwater resources and the employment of efficient irrigation methods are the primary factors for effective yields of wheat production (Thapa et al. 2019).

Turkey provides a quite suitable location and diverse ecology for wheat production (Gummadov et al. 2015). It is the world's eighth largest wheat producer (Özdoğan 2011)

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with a total production capacity of around 20 million tons (Gummadov et al. 2015). Wheat also has an important role in people's diets in Turkey. It is the most important crop supplying around 53% of the total calorie intake of Turkey's national population, while this ratio remains at 20% for the global average (Unakıtan and Aydın 2018). Water provided from the precipitation is estimated to be the most important factor affecting the yield of wheat production in Turkey (Keser et al. 2017). It has been reported that agricultural areas and total wheat harvest have decreased in recent years (Unakıtan and Aydın 2018). However, using suitable agricultural methods, fertilization and irrigation techniques, the grain yield of wheat has considerably increased (Gummadov et al. 2015).

Water footprint concept

Water footprint (WF) methodology has recently been acknowledged to be a strong tool contributing sustainable water management and planning works at the national, regional or watershed levels or for specific businesses or products. The water footprint of a product is defined as the total volume of freshwater employed through the whole supply chain of the product. Similarly, the water footprint of a geographically delineated area quantifies the total amount of consumed water within the region (Hoekstra et al. 2011). While traditional water use statistics measure only the direct water withdrawals, the water footprint methodology employs total water amounts used both directly and indirectly. Water footprint theory also investigates the type of processed water allocated by humans which are named as blue, green and grey water footprints. The blue component of the water footprint is defined as the total amount of surface and groundwater consumed by a water-intensive product or process. On the other hand, the green water footprint refers to the total amount of rainwater processed in any sector or area. Lastly, the grey water footprint is known as the total volume of freshwater resources required to dilute contaminants based on the water quality standards (Mekonnen and Hoekstra 2011a).

The national water footprint of production of a specific crop is defined as the total amount of consumed and contaminated water within the boundaries of the respective country to produce that crop. Exported products generated using the water resources of the country are also included. On the other hand, the water footprint of national consumption of a specific crop is the total amount of water processed through the production process whether it is produced locally or exported (Ercin et al. 2012). Two other important terms are originated based on these definitions which are internal and external water footprints. An internal water footprint refers to the amount of a nation's water resources to produce products and commodities. Similarly, an external water footprint becomes the consumption of other countries' water resources by the transfer of products and goods.

Virtual water transfer

The virtual water (VW) term has been conceptualized by Allan (1993) (Zhang et al. 2018a) and it is defined as the hidden water embedded in the products. International trade of goods and commodities have caused a large amount of virtual water transfer (VWT) (Masud et al. 2019). In recent years, VWT is considered to be an important parameter in saving water resources on a global scale also demonstrating the globalization of water resources (Elena and Esther 2010). Plantation area is quite important in agricultural products in terms of water use. A considerable amount of water resources can be saved if crops are grown in regions of low virtual water content (VWC) and then transferred to regions of higher VWC for consumption (Masud et al. 2019). On the other hand, water-abundant countries make profit by exporting these products (Mekonnen and Hoekstra 2010a). Today, many countries are externalizing their water footprints (Hoekstra and Mekonnen 2012).

Literature review

Water footprint assessments can be provided based on field studies, modeling studies, remote sensing or a combination of these techniques (Mekonnen and Hoekstra 2014). Initial water footprint analyses were about global water trade and its quantification. However, more recent studies have mainly concentrated on blue, green and grey WF components of certain crops at specific geographically delineated areas (Lovarelli et al. 2016). Mostly investigated crops for water footprint analyses are cereals, especially wheat and maize (Lovarelli et al. 2016). Wheat has gained special attention in scientific studies because of its high cultivation ranges and water consumption. Many studies of wheat's water footprint provide spatial and temporal quantifications, applying variability, sensitivity and uncertainty analyses and investigating climate change impacts and irrigation techniques.

In addition to the detailed studies on the global assessment of green, blue and grey WF of wheat (Mekonnen and Hoekstra 2010a), the water footprint of wheat has been quantified in China by (Luan et al. 2018) using a soil and water assessment tool. Total blue and green water use by wheat in China has also been analyzed by Cao et al. (2014). A water footprint assessment of wheat and other main cereals for Iran was provided by Ababaei and Etedali (2017). The total water footprint of wheat produced in Iran also has been investigated by Ababaei and Etedali (2014) with special emphasis on irrigation losses which are defined as white water. Similarly, there have been different studies assessing water footprints of wheat grown at different geographical areas such as Central Asia (Aldaya et al. 2010) and Italia (Casolani et al. 2016).

On the other hand, Gobin et al. (2017) provided a variability analysis of the water footprint of arable crop production in Europe. Also, the temporal variability of the water footprint of cereal production in Canada was studied by Zhao et al. (2019). Again, Zhuo et al. (2014) provided a sensitivity and uncertainty analysis of wheat and some other important crops. The effect of climate change on wheat's water footprint has been assessed by Garofalo et al. (2019). Wang et al. (2015) evaluated the impact of the change in growing land areas for wheat in China. The effect of soil mulching and drip irrigation on the water footprint of wheat was investigated by Nouri et al. (2019). Global sensitivity of water footprint estimations of crop production as well as wheat was discussed by Tuninetti et al. (2015). Wheat's crop ET was quantified and mapped for India (Rawat et al. 2017). Consequently, Zhuo et al. (2016) studied the benchmarks of wheat's production water footprint for different environments.

Contribution and scope of the study

Despite its high contribution to global wheat production, increasing population and strong wheat-based diet (Özdoğan 2011), quantitative, comparative and up-to-date analyses on blue and green water footprint and virtual water transfer of wheat production in Turkey are not available. The main scope of this study is to analyze national blue and green water footprint of wheat production, consumption and virtual water transfer in Turkey. The analyses cover 11 years between 2008 and 2019. In the present study, district-based statistics of wheat's total production, harvested area and yields have been used. Thus, monthly and spatially average crop evapotranspiration (ET_c) amount for 81 districts across Turkey has been generated by applying geostatistical analysis tools to the ground data of 229 meteorological stations ("Spatial interpolation of ET*c*" section). Ordinary Kriging methods have been used by ArcGIS software for the spatial interpolations. The total WF of wheat production, virtual water contents, crop water requirements, blue and green evapotranspiration amount have been calculated for each district using the water footprint methodology ("WF of wheat production in Turkey" section). The crop water requirement (CWR) approach has been employed for the blue and green ET modeling. Obtained results on WF of production have been compared across cities and discussed using precipitation, production and yield averages. On the other hand, the virtual water transfer regarding the international wheat trade of Turkey has been investigated, quantified and discussed ("WF of wheat consumption and virtual water trade" section). National and global water-saving or deficits have been outlined. To the author's knowledge, this is the first up-to-date assessment of the water footprint of wheat production, consumption and virtual water trade of Turkey using a comprehensive approach.

Materials and methods

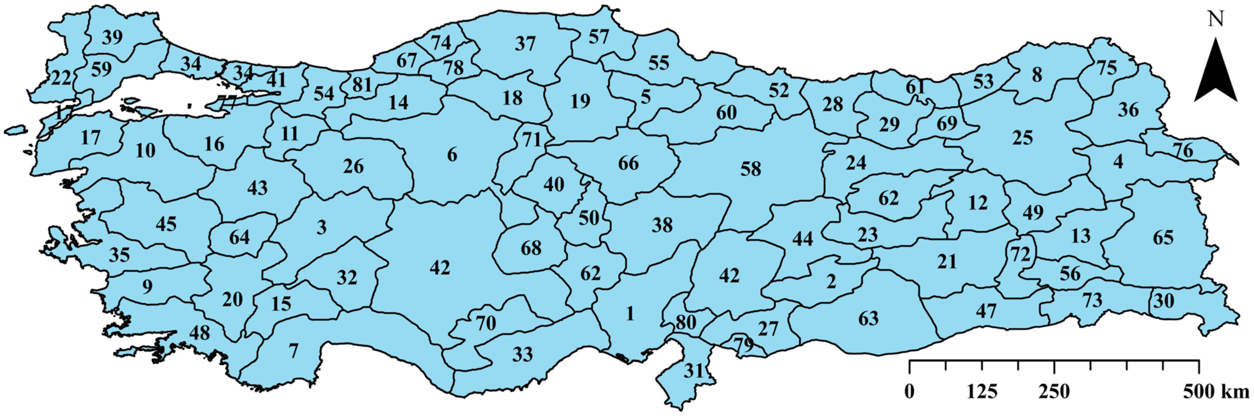
Study area

Turkey (Fig. 1) is located at Western Asia and partly in Europe (Dewndey and Yapp 2019). The average elevation is around 1132 m which is greater than Asia and Europe (TSHW 2019). The population was slightly over 82 million people, in 2018 (TSI 2019). The total surface area is about 769,600 km^2 excluding reservoir and natural lakes. Half of the total land area is mountainous. 36% of the surface area is suitable for agriculture, in which 5.8 million hectares are irrigated (TSHW 2019).

The country is located between the subtropical and temperate zones. It is under the influence of polar air masses in winter and tropical air masses in summer (Sensoy et al. 2008). Four different climate zones (terrestrial, Mediterranean, Marmara and Black Sea climates) are determined by the surrounding sea on three directions, the extent of mountains and diversity of landforms (Sensoy et al. 2008). The south of Turkey is influenced from the sub-tropical Mediterranean climate while on the north side Black Sea climate occurs with rain in all seasons (TSHW 2019). Since the inner regions are surrounded by mountains, the terrestrial climate is dominated with a little amount of rainfall and high variations at daily and yearly temperatures. As a whole, it is said that the semi-arid climate is experienced in Turkey (TSHW 2019). The precipitation, wind and temperature amount vary based on the climate parameters.

Long-term average annual precipitation is around 648 mm in Turkey, but this average has reportedly decreased by around 29 mm since 1900 (Sensoy et al. 2008). The spatial distribution of precipitation over Turkey shows great variations decreasing from coastal belts to the interior, having a steep gradient over the Northern Anatolia and Taurus mountains (Turkes 1996). While the coastal margins receive a high range of precipitation with around 2200 mm in Rize, the rainfall amounts are quite low at the interior regions, with, for example, average precipitation of around 320 mm in the province of Konya (Sensoy et al. 2008).

A latitude difference of 6° between the north and the south of Turkey causes high variations in temperature, thus evapotranspiration varies greatly (TSHW 2019). Annual reference evapotranspiration (ET_0) varies between 285 and 1200 mm through Turkey (TSMS 2019) with an average value of 902 mm (Şimşek et al. 2019). While the southern coasts experience high evapotranspiration rates, the lowest ET_0 is observed in north-eastern locations.



Province names:

1 Adana
2 Adıyaman
3 Afyon
4 Ağrı
5 Amasya
6 Ankara
7 Antalya
8 Artvin
9 Aydın
10 Balıkesir
12 Bingöl
13 Bitlis
14 Bolu
15 Burdur
16 Bursa
17 Çanakkale
18 Çankırı
19 Çorum
20 Denizli
21 Diyarbakır
23 Elazığ
24 Erzincan
25 Erzurum
26 Eskişehir
27 Gaziantep
28 Giresun
29 Gümüşhane
30 Hakkari
31 Hatay
32 Isparta
34 İstanbul
35 İzmir
36 Kars
37 Kastamonu
38 Kayseri
39 Kırklareli
40 Kırşehir
41 Kocaeli
42 Konya
43 Kütahya
45 Manisa
46 Kahramanmaraş
47 Mardin
48 Muğla
49 Muş
50 Nevşehir
51 Niğde
52 Ordu
53 Rize
54 Sakarya
56 Siirt
57 Sinop
58 Sivas
59 Tekirdağ
60 Tokat
61 Trabzon
62 Tunceli
63 Şanlıurfa
64 Uşak
65 Van
67 Zonguldak
68 Aksaray
69 Bayburt
70 Karaman
71 Kırıkkale
72 Batman
73 Şırnak
74 Bartın
75 Ardahan
76 Iğdır
78 Karabük
79 Kilis
80 Osmaniye
81 Düzce

Fig. 1 Studied area and provinces (numerical values are formal plate numbers of provinces)

Methodology

Water footprint of crop production

In this study, wheat's green and blue water footprint and virtual water transfer are investigated using the methodology reported by Hoekstra et al. (2011). The method is based on the water footprint network (WFN 2019) and ISO 14046 (ISO 14046 2017). The total water footprint of any product within a geographically delineated area can be calculated by multiplying the virtual water content with the production mass (Eq. 1). Virtual water content (VWC, m^3/ton) is defined as the volume of water embedded per unit mass of a product. In the water footprint theory, it is a common way to evaluate VWCs separately such as green and blue in order to reveal the effect of precipitation and surface/ground waters (Eq. 2). Crop water use (CWU, m^3) is defined as the total amount of consumptive water use of any crop in a planted area (Eq. 3). Measurement or estimation of evapotranspiration and irrigation quantities are vital for an accurate approximation of CWU. In this study, crop water requirement (CWR) model (Smith 1992) has been employed for green and blue evapotranspiration modeling ("CWR model" section).

$$\mathrm{WF}_c = \mathrm{VWC} x c \tag{1}$$

$$\mathrm{VWC} = \mathrm{VWC}_{\mathrm{green}} + \mathrm{VWC}_{\mathrm{blue}} \tag{2}$$

$$\mathrm{VWC} = \frac{\mathrm{CWU}}{Y} \tag{3}$$

where, WF_c is the total water footprint of crop production (m^3/year), c is the production amount (tons), VWC, $\mathrm{VWC}_{\mathrm{green}}$ and $\mathrm{VWC}_{\mathrm{blue}}$ are total, green and blue virtual water contents, respectively (m^3/ton), Y is the crop's yield (ton/ha), CWU is the crop's total water use (m^3/ha).

CWR model

CWR (crop water requirement) is defined as the total water demand of any crop to meet the evapotranspiration losses. The model assumes that water need of crop is fully met and the development of the crop is not affected by water shortages (Hoekstra et al. 2011); thus, the crop water use and crop water requirements become equal. The model is extensively used to find the water footprint of crop production, especially at large study fields where it is hard to include the irrigation activities. CWR model assumes that crop's blue water requirement (irrigation) is zero when effective rainfall is higher than the total crop evapotranspiration. By the definition, the blue water requirement becomes the difference between crop evapotranspiration and effective rainfall (Eq. 4). The green component of the crop water use is accepted to be the minimum of crop evapotranspiration and effective rainfall (Eq. 5). Consequently, the effective rainfall (P_{eff}) is defined as the total rainfall depth required by the crop through its growing periods (Patwardhan et al. 1990; Aldaya and Llamas 2008). In this study, the USDA-SCS (USDA-SCS 1993) method has been employed for P_{eff} modeling (Eq. 6).

$$\mathrm{CWU_{blue}} = \mathrm{ET}_{c,\mathrm{blue}} = \ max\left(0, \mathrm{ET}_c - P_{eff}\right) \tag{4}$$

$$\mathrm{CWU_{green}} = \mathrm{ET}_{c,\mathrm{green}} = \ \min(ET_c, P_{\mathrm{eff}}) \tag{5}$$

$$P_{\mathrm{eff}} = \left\{\begin{pmatrix} P(125-0.2P)/125; & P \leq 250\ \mathrm{mm} \\ 125 + 0.1P; & P > 250\,\mathrm{mm} \end{pmatrix}\right. \tag{6}$$

where, $\mathrm{CWU_{blue}}$ and $\mathrm{CWU_{green}}$ are the blue and green components of crop water use, ET_c, $\mathrm{ET}_{c,\mathrm{green}}$ and $\mathrm{ET}_{c,\mathrm{blue}}$ are total, green and blue evapotranspiration, P is the monthly precipitation and P_{eff} is the effective rainfall.

Crop evapotranspiration (ET_c)

Evaporation (ET) is the process of vaporization of water from ground or vegetated surfaces and is mainly expressed in terms of mm/day which is known as the evapotranspiration height. Various classifications have been developed for ET modeling. Reference crop evapotranspiration (ET_0) and the crop evapotranspiration under standard conditions (ET_c) are the most used concepts in the scientific literature. ET_0 is defined as the evaporation height of hypothetical grass surface having specific characteristics and sufficient water input. ET_0 represents the evaporative power of atmosphere and it is essentially used in water resources management studies (Kamali et al. 2015) due to being independent from crop type. Different methods have been developed to evaluate the reference evapotranspiration. However, FAO-Penman Monteith method is accepted as the sole method for ET_0 estimation (Widmoser 2009; Sentelhas et al. 2010). On the other hand, the crop evapotranspiration under the standard conditions, ET_c is defined as the evapotranspiration height of any crop under the optimum health, water and productivity conditions (Allen et al. 1998).

Mainly, ET_0 is calculated by inputting the site-specific solar radiation, maximum and minimum air temperatures, relative humidity and wind speeds to the FAO-Penman Monteith equation (Zhang et al. 2018b). On the other hand, the ET_c is calculated by employing dimensionless crop coefficients (K_c) and ET_0 (Eq. 7). The crop coefficients are experimentally averaged parameters over four different development periods which are initial, development, mid-season and late-season stages. K_c values reflect the crop's characteristics at corresponding location and climate and distinguishes it from the reference grass (Allen et al. 1998). It is obvious that the WF of any crop is greatly affected by the crop evapotranspiration and effective rainfall amounts (Eqs. 1–6). Therefore, accurate and precise measurement and estimation of these two parameters pose vital importance.

$$\mathrm{CWR} = \mathrm{ET}_c = K_c \mathrm{ET}_0 \tag{7}$$

Spatial interpolation

Station-based observations are relatively more accurate than spatial data. Hence, ground meteorological data is more extensively used than the remotely sensed estimations (Dalezios et al. 2002). However, spatial continuous data plays a significant role in planning and management studies (Li and Heap 2008) in order to predict data for ungauged stations, to obtain continuous surface maps and to develop data for discretized surfaces such as districts or provinces. Spatial interpolation tools including geostatistical models are powerful tools to estimate continuous data in water resources, ecology, agriculture, soil science, marine and environmental and other disciplines (Li and Heap 2008). In this study, the Kriging method which is reported to be the most recommended and effective spatial interpolation tool (Zimmerman et al., 1999, Li and Heap, 2011) has been used to obtain spatial continuous data of crop evapotranspiration.

Kriging is a common name of the geostatistical interpolation methods based on generalized least squares regression algorithms (Li and Heap 2008), and it is used for mapping and contouring the regionalized variables (Dalezios et al. 2002). The method can handle many problems which cannot be modeled by traditional approaches (Oliver and Webster 1990). It has been extensively used for estimation of evapotranspiration and other climatic parameters (Sousa and Pereira 1999; Dalezios et al. 2002; Liang et al. 2008; Raziei and Pereira 2013; Kamali et al. 2015).

Virtual water transfer of wheat

In spite of traditional approaches, the water footprint methodology also takes the imported and exported water amount into account due to the international transfer of commodities; which is commonly called virtual water transfer (VWT) or virtual water flow.

In this study, the international transfer of virtual water has been estimated based on the methodology proposed by Hoekstra and Chapagain, (2008) and Hoekstra et al. (2011). VWT can be calculated by multiplication of trade volumes (ton/year) to the VWC of the specified crop (Chapagain and Hoekstra 2008) in producing country (Eq. 8). The national water saving ($\mathrm{WS_{national}}$) is defined as the difference of imported and exported trade volumes times the VWC of national production (Eq. 9). The global water saving ($\mathrm{WS_{global}}$) through the international trade is evaluated by the multiplication of the product's trade volume to the difference between the

VWC at importing country and VWC at the exporting country (Mekonnen and Hoekstra 2010a) (Eq. 10). Therefore, the global water saving becomes the difference between the water productivities of the trading partners (Hoekstra et al. 2011). Negative values of WS imply the water loss. Virtual water balance is defined as the total import minus total export of virtual water (Hoekstra et al. 2011) (Eq. 11). Positive virtual water balance or virtual water surplus is defined as the case of a country's imported virtual water is greater than the exported virtual water.

Similarly, negative virtual water balance or virtual water deficit is defined for the inverse case (Zhang et al. 2018a). A certain amount of virtual water surplus is a desired situation in order to decrease the water shortage problems and to sustain the economic developments of the importing country (Zhang et al. 2018a). On the other hand, the national water dependency (virtual water import dependency, WD) is defined as the ratio of external water footprint to the water footprint of national consumption (Hoekstra et al. 2011) (Eq. 12). Finally, the national water self-sufficiency (WSS) is defined as the ratio of internal water footprint to the WF of national consumption (Eq. 13). Low range of WSS values approximating to zero implies that the nation externalized the water footprint of that product to a great extent (Hoekstra et al. 2011).

$$\mathrm{VWT}\left[\frac{\mathrm{m}^3}{\mathrm{yr}}\right] = T\left[\frac{\mathrm{ton}}{\mathrm{yr}}\right] \times \mathrm{VWC}\left[\frac{\mathrm{m}^3}{\mathrm{ton}}\right] \tag{8}$$

$$\mathrm{WS}_{\mathrm{national}} = \left(\mathrm{T}_{\mathrm{import}} - \mathrm{T}_{\mathrm{export}}\right) \times \mathrm{VWC} \tag{9}$$

$$\mathrm{WS}_{\mathrm{global}} = T \times \left(\mathrm{VWC}_{\mathrm{import}} - \mathrm{VWC}_{\mathrm{export}}\right) \tag{10}$$

$$\mathrm{VW}_{\mathrm{balance}} = \mathrm{VW}_{\mathrm{import}} - \mathrm{VW}_{\mathrm{export}} \tag{11}$$

$$\mathrm{WD}[\%] = \frac{\mathrm{WF}_{\mathrm{external}}}{\mathrm{WF}_{\mathrm{consumption}}} \times 100 \tag{12}$$

$$\mathrm{WSS}[\%] = \frac{\mathrm{WF}_{\mathrm{internal}}}{\mathrm{WF}_{\mathrm{consumption}}} \times 100 \tag{13}$$

where, VWT is the virtual water transfer of wheat from exporting country to the importing country, T is the commodity's trade volume (wheat), VWC is the virtual water content of the transferred wheat, $\mathrm{WS}_{\mathrm{national}}$ is the national water saving, $\mathrm{WS}_{\mathrm{global}}$ is the global water saving, $\mathrm{VW}_{\mathrm{balance}}$ is the virtual water balance, WD is the national water dependency and WSS is the national water self-sufficiency.

Data

Wheat's production weights, plantation area and yield data have been obtained from the Turkish Statistical Institute (TSI) database (TSI 2019). The specified data is based on the provincial boundaries and reflects the annual averaged parameters for each of 81 provinces in Turkey for the time period of 2008–2019. This data has been used to evaluate virtual water contents and total water footprints which are specified in Eqs. 1–3.

Evapotranspiration which reflects the blue and green water requirement of crops has a vital importance in water footprint analyses ("CWR model" section, Eqs. 4–5). In this study, wheat's crop evapotranspiration under standard conditions (ET_c) data which is published by TAGEM (Turkey's General Directorate of Agricultural Research and Policies) and DSI (Turkish State Hydraulic Works) (TAGEM, 2017) has been used. In the mentioned work, various crop's ET_c heights of each decade (10 days) have been calculated based on long-term averaged daily reference evapotranspiration and regional crop characteristics for Turkey. ET_0 amounts have been evaluated using long-term meteorological data (daily minimum, average and maximum temperatures, relative humidity, wind speed, solar radiation and sunshine hours) which is attributed to MGM (Turkish State Meteorological Service). It has been noted that employed meteorological data has been quality controlled and the missing data have been completed based on the guidelines published by FAO (Allen et al. 1998). Then, reference evapotranspiration heights have been calculated employing FAO-Penman Monteith model. In the mentioned work, the crop coefficients and development periods of various crops for different stations have been approximated using the field studies and verified based on international reports, scientific studies and models reported by FAO (Allen et al. 1998) considering 25 different sub-climate zones in Turkey (TAGEM, 2017).

The spatially averaged monthly precipitation data for 81 districts (for 2008–2019) has been obtained from the MGM (Turkish General Directorate of Meteorology) (MGM 2019). The employed rainfall data is based on point precipitation measurements at 255 meteorological stations across Turkey. The spatial interpolation was made by the Kriging method and validated with other interpolation tools (MGM 2019). The details of the spatial interpolation associated with this data are reported by Sensoy et al. (2007).

The virtual water content of wheat for various countries were obtained from UNESCO-IHE (Institute for Water Education) Value of Water Research Report Series No. 50 (Mekonnen and Hoekstra 2011b; Mekonnen and Hoekstra 2011c) in which the national water footprints were calculated for 1996–2005 using the data of various crops generated by Mekonnen and Hoekstra, (2010b) which is based on a gridded daily soil-water balance model and Penman-Monteith reference evapotranspiration model. Finally, wheat trade statistics (import and export quantities per year) for 2008–2019 were obtained from the ITC's (International Trade Center) Trade Map database (ITC 2019).

Results

Spatial interpolation of ET_c

Penman-Monteith model employs climatic information of discrete points in which the latitude and altitude of the meteorological stations should be specified (Allen et al. 1998). Accordingly, estimations of the reference and total crop evapotranspiration become spatially discontinuous. Determination of the continuous spatial ET distribution is essential for the majority of climatic and agricultural studies (Dalezios et al. 2002). In this study, Ordinary Kriging (OK) method was employed to obtain spatial distribution map of wheat's ET_c over Turkey and to get the monthly and annual averages for each of 81 districts within Turkey using discrete data of 229 stations ("Data" section). ArcGIS geostatistical and spatial analyst toolboxes were employed to get the local averages (Fig. 2).

The Kriging method assumes that the data is spatially auto-correlated. The autocorrelation test of the ET_c dataset employed within this study has been provided using Global Moran's I test (ArcMap 2019) with inverse distance, Euclidean method. A strong clustering pattern is observed at the total annual crop evapotranspiration with Moran's Index = 0.623, p value = 0, and z score = 19.63 which shows the existence of positive spatial autocorrelation. On the other hand, available global trends have been removed using first-order-polynomial function. Data that does not conform with the normal probability distribution has been optimized using log-transformation option of the ArcGIS software. Standard neighborhood type has been specified with a default value of the maximum and minimum number of neighbors to be 5 and 2, respectively. Consequently, the prediction errors have varied in each monthly dataset. Standardized root mean square error (RMSE) was around 0.94 for the annual evapotranspiration and was between 0.90 and 1.05 for each month. Figure 2 illustrates obtaining ET_c value of each province using OK method-based spatial analysis.

Spatially averaged evapotranspiration of wheat (ET_c) in Turkey has been calculated as 504 mm/year. Wheat's ET_c varies greatly over Turkey. Mainly high ET_c is observed at the east side which is called as Eastern Anatolian Region. Among the provinces, the highest ET_c is estimated to be in Muş and Van which is above 680 mm/year. On the other hand, the coastal sides are of lower ET_c, as expected. Hatay, Kilis and Osmaniye experience lowest ET_c which approximates to 410 mm/year. Consequently, the highest wheat cultivation exists at the inland regions of Turkey which have moderate ET_c, characteristically around 450–500 mm/year.

WF of wheat production in Turkey

WF of national production

In this study, total blue and green water footprint of wheat production in the study area has been found as 39.3 Gm^3/year for the last 11 years. Using the outcomes of this study and the global report provided by Mekonnen and Hoekstra, (2010a), it has been estimated that around 4.0% of global consumptive (blue and green) WF of wheat production is provided from Turkey (Table 1).

Comparison of the green, blue and total virtual water contents (m^3/ton) of wheat produced in Turkey, neighboring countries, Tigris-Euphrates basin and major wheat-producing countries has been illustrated in Fig. 3. Turkey is one of the countries having substantial amount of WF. Accordingly, average VWC (blue and green components) of wheat production in Turkey was found as 1909 m^3/ton which is slightly higher than the world average. Also, total and blue VWC of wheat is found to be lower than Iraq, Iran and average of Tigris-Euphrates river basin where the country is surrounded from the south and the east. On the other hand, the blue VWC is found 2.2 times of the world average which represents that a relatively higher amount of surface and groundwater utilization is required for wheat cultivation in Turkey. Similarly, in Turkey, the blue VWC is higher than that of major wheat-producing countries such as China, Canada and USA, as an expected situation when the country's position and climate conditions are considered.

WF variation within Turkey

Annual and spatial averaged precipitation, wheat production, yields and harvest area for 81 districts are illustrated in Fig. 4. It can be seen that wheat production is concentrated in the inland and central regions of Turkey due to availability of arable lands, wheat's adaptation to specific climatic conditions and reasonable ET_c rates (Fig. 3). On the other hand, productivity (yield) is higher on the coastal zones as a consequence of high rainfall rates.

ET (blue+green), VWC, blue CWU and WF maps of Turkey are given in Fig. 5. Accordingly, Konya and Ankara are responsible for around 9.3% and 5.8% of Turkey's WF of wheat production, respectively. Other most important cities in terms of high footprints are Diyarbakır, Yozgat, Şanlıurfa and Sivas. A total of 30% blue and green water of national wheat production in Turkey is consumed within these six districts. The lowest VWC of wheat is in Hatay which is a southern district with a considerably higher productivity rate of 3.95 tons/ha. The amount of total water footprint is related to the crop's productivity, rainfall amount, evapotranspiration rates and other climatic, soil and agricultural conditions. However, the most important parameter affecting the virtual water content seems to be the production yields. The negative correlation between the productivity rates and VWCs can also be observed from Figs. 4 and 5.

In spite of high-temperature characteristics and low precipitation rates, Şanlıurfa district has a remarkable place where wheat's productivity is around 3.01 tons/ha

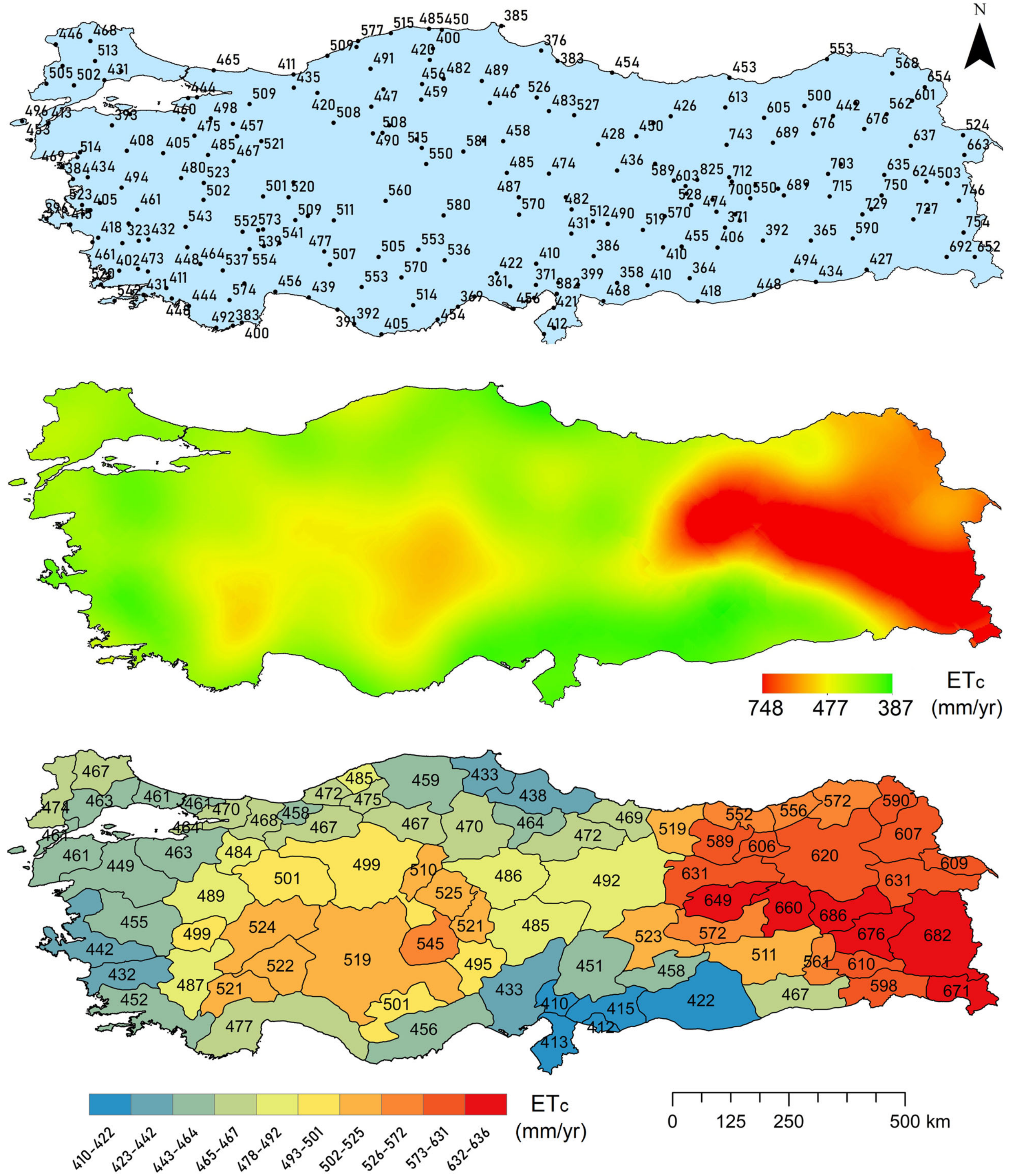


Fig. 2 Obtaining annual ET_c distribution of wheat within Turkey (from top to bottom; station observations (TAGEM 2017), spatial interpolation and getting the zonal statistics of annual average for each district)

and VWC is 1387 m^3/ton. Therefore, Şanlıurfa and its nearby districts such as Diyarbakır, Mardin, Adıyaman and Batman (Southeastern Anatolian Region) should be considered as potential regions where the wheat production could be promoted to decrease freshwater dependency and to increase yield. On the other hand, high VWC (as well as the blue component) of wheat in Ankara which is 2155 m^3/ton should be taken into

Table 1 Wheat's annual average water footprint statistics for Turkey (2008–2019)

	Total water footprint (Gm^3)	Shares of total WF (%)	Average VWC (m^3/ton)	WF per harvested area (m^3/ha)	WF per total area (m^3/ha)	Per capita (m^3/cap)
Green	23.9	61	1161	3037	310	291
Blue	15.4	39	748	1957	200	188
Total	39.3		1909	4994	510	479

account by the water and agricultural management authorities.

Blue VWC should also be considered for hotspot identification in terms of wheat production. The blue VWC of wheat greatly varies across Turkey between 151 and 2783 m^3/ton. Hatay, Osmaniye and Adana (Çukurova Region) are the most important districts where the blue water dependency of wheat is considerably low necessitating insignificant irrigation volumes. On the other hand, these and surrounding districts are also highly responsible for fruit, vegetable and maize production of Turkey (Keskin and Sekerli 2016). Wheat production could be alternatively promoted in the Southeastern Anatolian Region where the blue CWU is still lower than the Turkey average in order to increase the agricultural diversity of Turkey. This outcome shows that it is very important to have agricultural planning based on a holistic approach considering the economic return, protecting the regional and national water resources, lower pollution levels, existence of suitable agricultural fields and productivity rates.

WF of wheat consumption and virtual water trade

Turkey's average annual wheat consumption was around 24.7 million tons between 2008 and 2019 (Fig. 6). About 18% of wheat consumption corresponding to 4.3 million tons is imported. Russia is the most important country providing 62% of total wheat imports. Kazakhstan, Ukraine, Lithuania, USA and Germany are the other important countries for Turkey in terms of wheat supply, respectively. The total wheat export of Turkey is around 0.19 million tons. Around 68% of exports are shipped to Italy, Syria, Israel, Bangladesh, Egypt and Iraq.

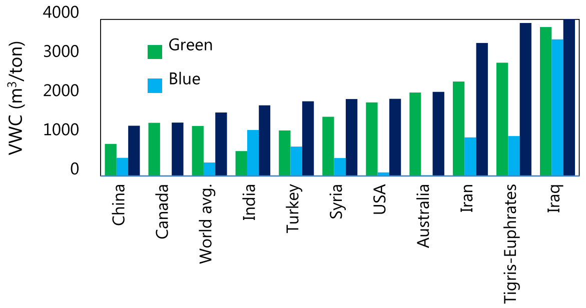


Fig. 3 Green, blue and total virtual water contents of wheat in Turkey (this study), neighboring regions and major wheat producing countries. (Other countries' data is based on Mekonnen and Hoekstra, (2010a))

In this study, the annual blue and green WF of wheat consumption of Turkey is estimated as 47.9 Gm^3/year in which 32% is blue water. WF of internal consumption, which is known as the total WF of national production minus the virtual water exports, is 38.9 Gm^3/year. About 81% of wheat's total consumptive water use is covered by internal consumption, and the remaining 19% corresponding to 9.2 Gm^3/year is imported. Overall illustration and comparison of blue and green water footprints of wheat production, consumption, imported and exported virtual waters have been provided in Fig. 7. Also, Turkey's virtual water import for wheat is illustrated in Fig. 8. A total of 93% VW import is provided from Russia, Kazakhstan, Ukraine, USA, Lithuania, Mexico and Canada. Russia supply around 6.3 Gm^3/year virtual water corresponding to 68% of wheat's total imported water. On the other hand, Kazakhstan exports around 1.2 Gm^3/year virtual water to Turkey together with 0.35 million tons of wheat trade. It should be noted that the majority of virtual water import (98%) is composed of green water due to high green water shares of wheat production in Russia, Kazakhstan and other abovementioned major wheat supplying countries.

Compared with the VW import, Turkey's VW export is insignificant with around 0.37 Gm^3/year. National blue and green virtual water exports for wheat production are illustrated in Fig. 9. Accordingly, 75% of virtual water export is provided to Italy, Syria, Israel, Bangladesh, Egypt, Iraq and Tunisia. Turkey's blue and green VW transfer to Italy is around 60 Mm^3/year. Turkey sends around 58 Mm^3/year and 42 Mm^3/year of virtual water to Syria and Israel, respectively. Around 39% of total exported VW is composed of blue water. Turkey's blue water transfer regarding the wheat export becomes 144 Mm^3/year.

National and global water savings

National water saving shows the degree of saving a country's water resources by importing water-intensive products rather than generating them domestically (Chapagain 2006). On the other hand, global water resources can be saved if the products are produced at the regions of lower virtual water (which is also referred as high water productivity) and shipped to the regions of higher VWC. In this study, the national and global water savings were calculated using Eqs. 9 and 10. Wheat's

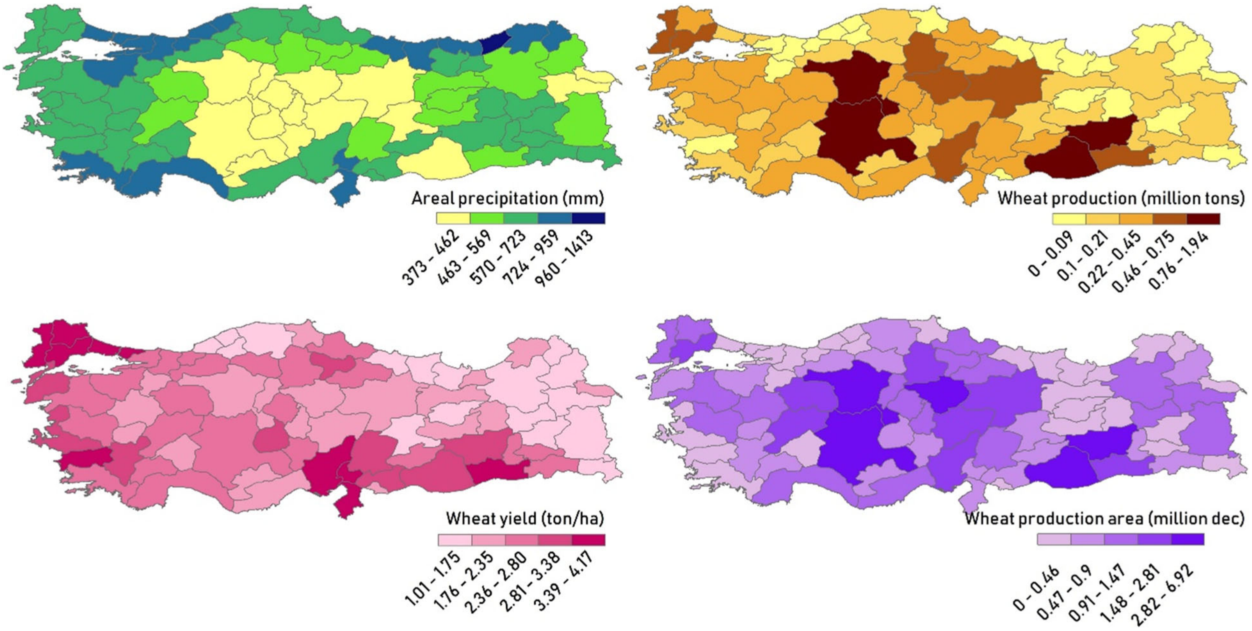


Fig. 4 District-based annual precipitation, wheat production, area and yield maps (city codes and names are reported in provincial map, Fig. 1)

high import rates resulted in a positive national water saving value (water gain) for Turkey where the total $WS_{national}$ is calculated as 7.8 Gm^3/year. Similarly, Turkey gains around 5.1 Gm^3/year water from the wheat transfer with Russia. While the highest virtual water export is provided to Italy, the national water loss becomes maximum with the trade to Syria and Israel due to the impact of net virtual water balance. Total national water loss regarding the wheat trade by these two countries is around 99.4 Mm^3/year. Based on the VW imports and exports, the national water import dependency (WD) of wheat production in Turkey is calculated as 18.9%. Similarly, the national water self-sufficiency (WSS) is found as 81.9% which shows high capability of national water supply for wheat.

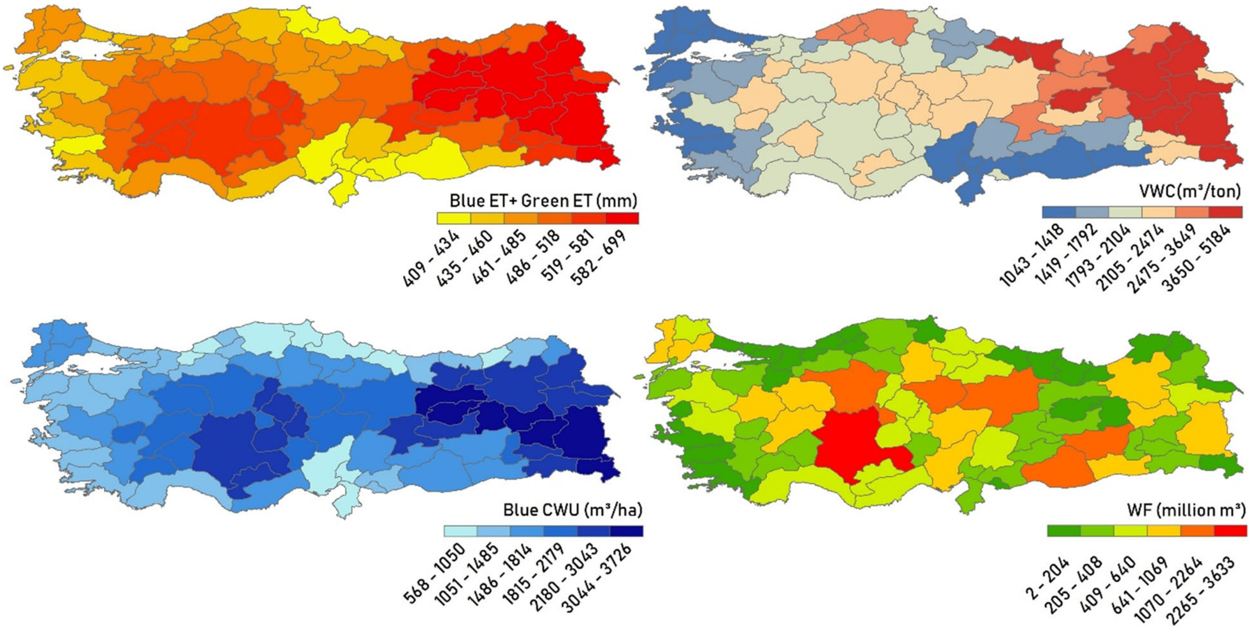


Fig. 5 Wheat's blue and green ET, VWC, blue CWU and WF maps through Turkey's provinces (city names are reported in provincial map, Fig. 1)

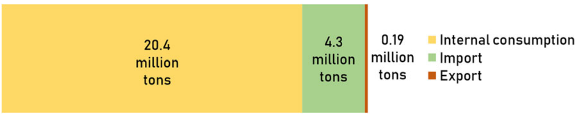


Fig. 6 Wheat production, consumption and trade statistics in Turkey

The contribution of wheat trade between Turkey and various countries to the global water savings is illustrated and compared in Fig. 10. Accordingly, the net global water saving is estimated as −1.09 Gm^3/year for the international wheat trade of Turkey which implies a net water loss. The main reason behind this virtual water loss is sourced from the large volumes of wheat trade of Turkey from Russia and Kazakhstan. The consumptive VWC of wheat production in Russia is around 2357 m^3/ton, while in Turkey this value is 1909 m^3/ton. Thus, net global water saving for the wheat trade from Russia to Turkey becomes around −1.19 Gm^3/year. Similarly, the VWC of wheat produced in Kazakhstan is 3395 Gm^3/year and this country is the second largest virtual water provider to Turkey contributing to the global water saving as −0.52 Gm^3/year. The total value of negative virtual water savings (water loss) of wheat trade of Turkey becomes around 1.76 Gm^3/year. On the other hand, the virtual water trade of Turkey between Germany, Lithuania, Iraq, Hungary, Mexico, Canada and Ukraine has positive contributions to the global virtual water savings. Net wheat import of Turkey from Germany and Lithuania saves around 0.14 and 0.11 Gm^3/year of global water resources, respectively. The virtual water export of Turkey to Iraq saves around 74 Mm^3/year water. Consequently, net positive global virtual water saving becomes 0.66 Gm^3/year.

Discussion

Comparison with previous studies

Mekonnen and Hoekstra (2010a) provided an extensive assessment reporting wheat's annual WF of majority of nations and large basins for 1996–2005. The outcome of the present study regarding wheat's national blue and green WF of production (39.3 Gm^3/year) is compatible with Mekonnen and Hoekstra, (2010a) having around 9% underestimation. The difference can be explained with the quality and time period of employed data, changes in precipitation, yield and production characteristics, as well as the employed model. On the other hand, the blue and green water footprint shares of Turkey were predicted as 61% and 39%, respectively. However, Mekonnen and Hoekstra (2010a) reported the blue water share of Turkey as 6.2% which is quite underestimated relative to this study. Although there are various reasons for this difference, the most effective parameter is believed to be the selected irrigation model. In their studies, Mekonnen and Hoekstra (2010a) employed a so-called grid-based dynamic water balance model, while in this study, CWR model has been used due to unavailability of national soil data of high resolution. The water balance-based models provide more accurate results (Hoekstra et al. 2011) by separately investigating the rain-fed and irrigated areas and utilizing the type and moisture content of the soil. However, CWR model is quite advantageous when the soil type data are unavailable assuming the crop water need to be equal to ET_C. It is also reported that the amount of consumptive WF (blue and green) is approximately equal for irrigated and rain-fed fields (Mekonnen and Hoekstra 2010a).

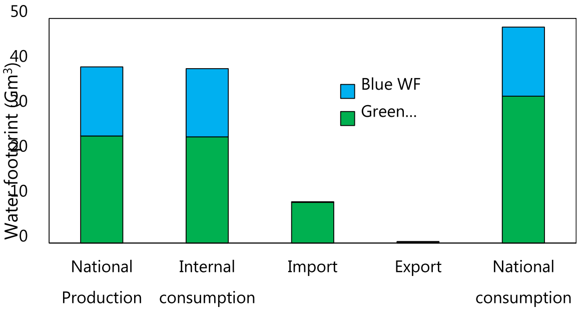


Fig. 7 Comparison of WF of wheat production, consumption and virtual water transfer in Turkey

Another study provided by Mekonnen and Hoekstra (Mekonnen and Hoekstra 2011b) reports total per capita water footprint of wheat's national consumption of Turkey as 510 m^3/year for 1996–2005. In this study, the sum of blue and green water footprints is estimated to be around 599 m^3/year for 2008–2019. On the other hand, to the author's knowledge, there is no detailed previous study analyzing the virtual water trade of wheat in Turkey. Total virtual water import and export of Turkey based on all agricultural crops is reported as 24.5 and 21.6 Gm^3/year, respectively (Mekonnen and Hoekstra 2011b). The findings of current study show that wheat trade provides a relatively high percentage of total VW import (38%) while it is insignificant for VW exports (1.7%).

The comparison of blue and green VWCs of wheat in Turkey and other important countries and surrounding basins is provided in the "WF of national production" section. Also, the WF in different provinces of Turkey were illustrated and discussed in the "WF variation within Turkey" section. The findings of this study and previous studies show that the crop water footprints can significantly vary (Mekonnen and Hoekstra 2014) across and within regions (Figs. 3, 4 and 5). This variation is originated from the combined impacts of region-specific agricultural and climatic conditions. It has been noted that the variability of crop production mainly depends on the yield and water use amount by 45% and 21%, respectively (Gobin et al. 2017). It is also reported that the

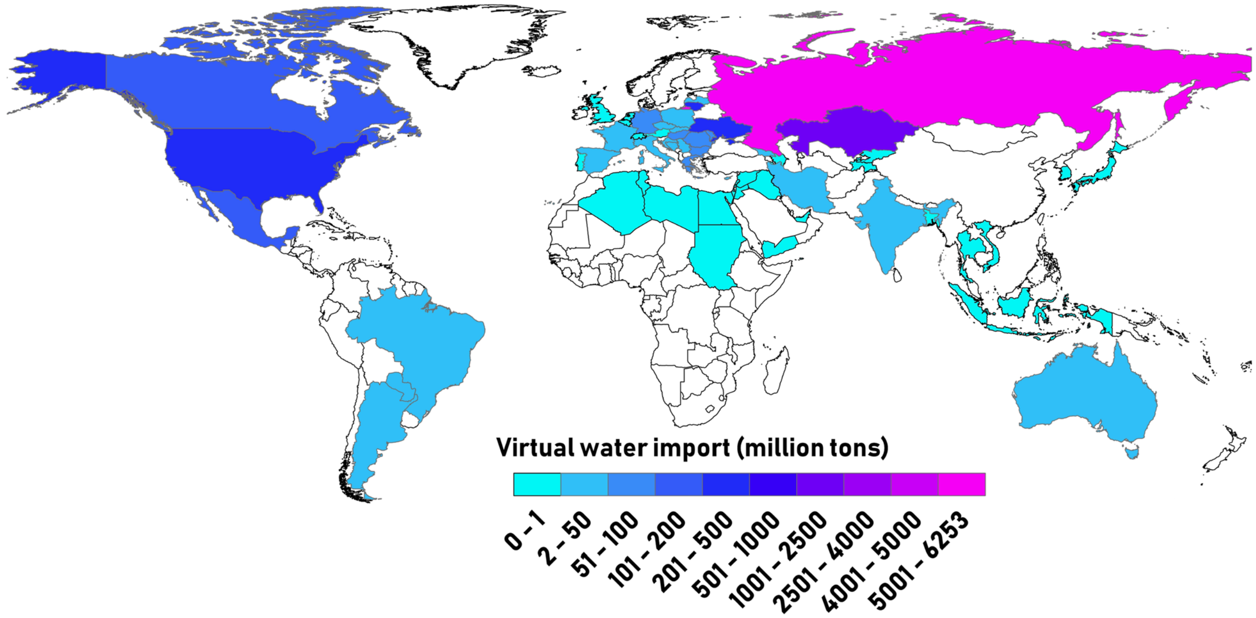


Fig. 8 Illustration of Turkey's virtual water imports

WF of wheat could increase up to five or six-fold at different locations across the neighboring countries (Gobin et al. 2017). It has been shown that the (variation of) green virtual water content of wheat across Europe could be 1108 ± 580 m^3/ton. Quality and characteristics of available data and capability of the employed models may also affect the delivered results (Mekonnen and Hoekstra 2014).

Grey water footprint

In this study, the grey water footprint has not been considered due to the unavailability of reliable provincial or national pollutant data. Ignoring the grey water footprint is one of the main limitations of this study. However, to date, the grey water footprint quantifications are based on very broad and preliminary approximations and assumptions (Franke et al. 2013). A detailed methodology

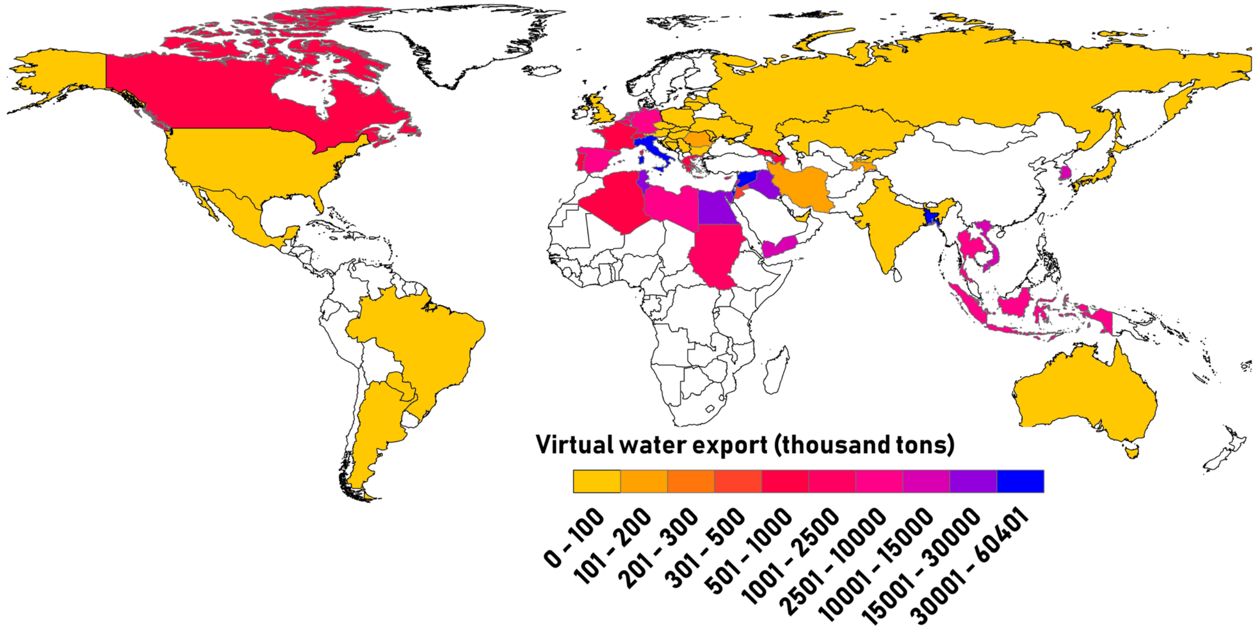


Fig. 9 Illustration of Turkey's virtual water exports

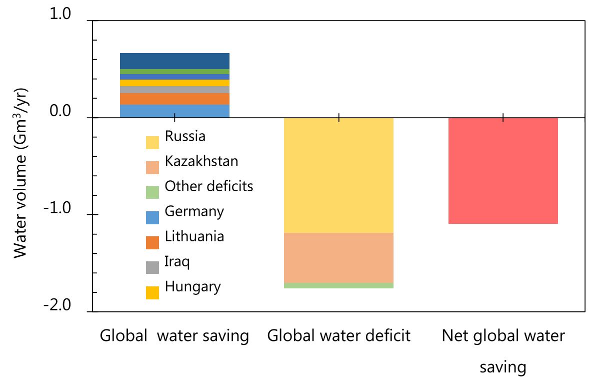


Fig. 10 Comparison of global water saving and deficit regarding the international wheat trade of Turkey

has not been proposed yet for more accurate analyses. Previous studies on grey water footprints of crop production employ non-point sources of fertilizer application yields, leaching fractions and maximum allowable pollutant concentrations (Laspidou, 2014). If multiple pollutants exist in the studied region, the largest calculated footprint is taken as the grey water footprint of the region (Johnson and Mehrvar 2019) which is generally caused by nitrogen emission. Similar studies mainly employ the country-specific data of all agricultural pollutants (Hu et al. 2018; Serio et al. 2018). Thus, a comprehensive approach is suggested for the grey water footprint quantification considering different types of contaminants regarding various crops' production processes. Nevertheless, average grey WF of crop production is reported to be around 9.9% in total WF, globally (Mekonnen and Hoekstra 2010b). On the other hand, grey water footprint of wheat production accounts for around 11% of total WF of wheat, globally. Consequently, the grey water footprint of wheat production in Turkey is reported to be 8.1% of wheat's total WF (3.8 Gm^3/year) (Mekonnen and Hoekstra 2010a).

Sensitivity and uncertainty of the model

The present study has been conducted based on the WF methodology that has been proposed by the water footprint network (WFN) and ISO 14046 (Hoekstra et al. 2011; ISO 14046 2017; WFN 2019). Basically, employed hydrological methods can have uncertainty levels due to input data, model assumptions, boundary conditions, calibration, etc. In most cases, the uncertainty of the employed model is of important concerns because the main outputs are used by the policy-makers, regulation and management authorities (Zajac 2010). Therefore, sensitivity and uncertainty analyses are recommended to be provided on the employed model and data. Uncertainty analyses are conducted in order to determine the overall uncertainty of model outputs due to uncertainties in the inputs, while sensitivity analysis determines the contribution of each input factor to the uncertainty of an output (Convertino et al. 2014). The lack of sensitivity and uncertainty analysis is one of the important limitations of this study. However, a few literature studies are available investigating the sensitivity and uncertainty of the WF of wheat at different spatial and temporal scale. The sensitivity and uncertainty analysis of WF (several crops including wheat) at Yellow River Basin has been conducted by Zhuo et al. (2014). They investigated the fractional changes of model inputs using once-at-a-time/sensitivity curve method. Also, the uncertainties of WF (due to precipitation, reference evapotranspiration, crop coefficients and crop calendar, etc.) were analyzed using Monte Carlo simulations. They showed that the sensitivity and uncertainty levels vary according to the crop type, and WF is mostly sensitive to ET_0 and crop coefficients (K_c). Furthermore, blue WF is found to be more sensitive than green WF. The uncertainties for total WF were reported to be about ±30% at 95% confidence level (Zhuo et al. 2014). Similarly, Tuninetti et al. (2015) studied on spatial variability of VWC of several crops including wheat, operating a first order sensitivity analysis using Taylor series. They reported that the spatial variability of VWC is mostly controlled by spatial patterns of crop yields with an average correlation coefficient of 0.74. The influence of evapotranspiration has been reported to be lower than the crop yield with a correlation coefficient of 0.34. Wheat is found to be the most sensitive crop to the growing period length. They also highlighted strong spatial heterogeneities inside climatic regions and at subnational scale (Tuninetti et al. 2015).

In addition to the abovementioned works, more scientific studies are required to be conducted on the sensitivity and uncertainty of WF accounts because most of the hydrological models have a non-linear and non-monotonic structure. Local and once-at-a-time methods are of limited use to evaluate the relative importance of uncertain input factors (Saltelli et al. 2008; Zajac 2010). Global sensitivity and uncertainty analysis (GSUA) which is irrespective of model assumptions of linearity and monotonicity has advantages over local, derivative-based and once-at-a-time approaches exploring the whole potential range of all uncertain model input factors (Zajac 2010). GSUA is reported to provide quite useful analytical framework for the uncertainty of any model output allowing the users to determine the most accurate model in terms of accuracy, complexity and uncertainty providing approximate predictions to the real system (Convertino et al. 2014). Basically, Morris (1991) and Sobol (1993) methods are recommended for GSUA, respectively (Convertino et al. 2014). Maximum entropy networks (MENets) which are frequently used in the fields of complexity and information sciences can also be applied to the WF model in order to make systematic comparisons among different data of any spatial and temporal scale (Servadio and Convertino 2018).

Reliability of the data

Water footprint studies analyzing relatively wide range of area mainly rely on the global gridded maps of evapotranspiration, crop statistics and characteristics, etc. which are generated or interpolated through GIS (geographical information systems) based on remote sensing techniques (Hoekstra et al. 2011; Mekonnen 2011; Zeng et al. 2012). The main disadvantage of these approaches is having higher errors due to misinterpretations of sensitive physical parameters relative to the measured data in place. In this study, the meteorological station data which have been collected and validated by the local/national authorities for the specific districts have been used.

The basic ET_c data used in this study is based on the observations of 229 ground meteorological stations. Existing data for all stations reported by Turkish General Directorate of Agricultural Research and Policies have been used. Spatial continuous map and zonal averages for each district were generated considering the meteorological stations inside the provinces and also employing the neighboring regions ("Spatial interpolation of ETc" section). It is believed that the basic data are sufficiently representative due to using the excessive number of stations. Also, the spatial interpolation techniques eliminate the non-homogenous distribution of stations especially in the regions of high wheat cultivation (inland regions). The contribution of irrigation is considered by the CWR model ("CWR model" section) which is a generally accepted method especially on large study fields where limited irrigation data is provided.

In the present study, the WF analysis has been conducted using aerial precipitation and crop production statistics between 2008 and 2019 ("Data" section). The crop evapotranspiration data is based on the ET_0 data that has been generated using long term averaged meteorological data of daily minimum, average and maximum temperatures, relative humidity, wind speed, solar radiation and sunshine hours. On the other hand, VWT analyses (both imports and exports) were provided using the trade data, meteorological data and crop production statistics for the same periods (2008–2019). It is obvious that WF of consumption, as well as the internal and external components of virtual water, is strongly based on the trade data and varies at temporal scale. In this study, the VW imports were calculated based on various nation's VWCs which are evaluated by Mekonnen and Hoekstra, (2011b, c) for 1996–2005, neglecting the temporal variations of other countries due to unavailability of data. Employing the updated VWCs of countries would provide more accurate results, for the further studies.

Conclusion

Water footprint parameters such as virtual water contents, imported and exported virtual water amounts, national and global water savings are important to be considered by national and international water management authorities. Many countries have now started to encourage analysis of water footprint of different area and products (Aldaya et al. 2019). Water footprint and productivity analyses especially on agricultural products are important in order to understand the economic arguments of the basins (Aldaya et al. 2019). This study is expected to increase the agricultural water allocation efficiency for better planning and management and contribute to the sustainability of national and global water resources.

Abbreviations

c: Crop's production amount (ton); CWR: Crop water requirement; CWU: Crop water use (m^3/ha); ET: Evapotranspiration (mm); ET_0: Reference evapotranspiration (mm); ET_c: Crop evapotranspiration; K_c: Dimensionless crop coefficient; OK: Ordinary Kriging method; P_{eff}: Effective precipitation (mm); T: Trade amount (ton); VW: Virtual water; $VW_{balance}$: Virtual water balance (m^3); VWC: Virtual water content (m^3/ton); VWT: Virtual water transfer; WD: Virtual water import dependency (%); WF: Water footprint (m^3); WF_c: Water footprint of crop production (m^3); WS_{global}: Global water savings (m^3); $WS_{national}$: National water savings (m^3); WSS: Water self-sufficiency (%); Y: Crop yield (ton/ha)

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Author's contributions

This study has been prepared by a single author AM. The author read and approved the final manuscript.

Author's information

No additional information.

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Please contact the author for data requests.

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The author declares that he has no competing interests.

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