Future virtual water flows under climate and population change scenarios: focusing on its determinants

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ABSTRACT

Water resources are under increasing pressure from population growth, socio-economic development, and climate change. The main user of freshwater is the agriculture sector, accounting for 70–80% of global water use. Consequently, increasing water productivity and reducing water use in this sector are vital for alleviating water scarcity. It has been alleged that domestic or international trade of water-consumed products from wet-provinces or countries to arid and semi-arid provinces or countries is one possible path to mitigate water shortage. In this regard, virtual water flows and their determinants in Iran are investigated in this paper. This study examines the main determinants of bilateral virtual water flows associated with international trade in agricultural goods among Iran and other countries using a gravity model of trade. The impacts of climate change and socio-economic change scenarios on the virtual water trade are simulated. The result of the gravity model indicated that bilateral virtual water trade flows are influenced by the classical determinants and all the mass-related variables (gross domestic product and population) are significant with expected signs. Finally, the result obtained from the simulation of climate and socio-economic change scenarios showed that under the pessimistic scenario of climate change and population growth rate of 0.98 and 0.44%, VW trade between Iran and other countries would increase by 41 and 66% in the periods of 2016–2045 and 2070–2099, respectively. As a consequence, identifying the appropriate countries for business interactions and adopting effective trade policies are very important and need attention soon.

Key words: climate and demographic change scenarios, determinants, Iran, virtual water trade, water footprint

HIGHLIGHTS

• Bilateral virtual water trade flows are influenced by the classical determinants and all the mass-related variables (gross domestic product and population).
• The size of the future virtual water flows was predicted under the climate and population change scenarios.
• The average annual temperature and the population of Iran, as the determinants of virtual water flows, have a positive and significant effect on the net virtual water flows.

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INTRODUCTION

Factors such as socio-economic development, population growth, and climate change have created major challenges for sustainability and food security as two of the most important societal concerns (Vorosmarty et al. 2000; Gleik 2008). In this regard, the water resources, which are essential for human life, sustainable livelihoods, and ecosystems, are under pressure. While certain areas of the world have abundant water, other areas suffer from water shortages. Iran is considered as one of the areas facing severe water scarcity. The water per capita in Iran was 5,570 cubic meters in 1962, which declined sharply to 1,876 cubic meters in 2008 and 1,688 cubic meters in 2017, which is lower than the world average (6,225 cubic meters) (Aquastat 2017; World Bank 2014). Various factors such as climate change and diversity, rapid economic development, widespread urbanization and pollution, and irrational agricultural policies may justify unprecedented pressure on water resources (FAO 2016). The current status of water resources in Iran and its governing trends and processes clearly illustrate the need for managing the demand and moderating water consumption. The agricultural sector, with the highest water consumption (80% of the total consumption; Rost et al. 2008), has focused on reducing water consumption. The improvement of water productivity is considered as the most important strategy to balance the declining supply and increasing demand for water resources. There are several ways to improve the productivity and increase water use efficiency. In the same vein, the international trade of the agricultural products is a way to improve the global water use efficiency through the virtual transfer of water resources to the water-stressed areas (Dalin 2014), which saves a significant amount of water resources globally or nationally (Chapagain et al. 2006). The water used in production processes is called virtual water, which is transferred in the form of trading the agricultural, livestock, and industrial products and is used as a strategic tool to increase water access in areas facing water constraints (Mubako 2011).

In the case of the products containing virtual water, trade is regarded as a means for transferring water resources between regions. In addition, the domestic and international food trade saves water on a national scale by encouraging the virtual water exchanges from provinces or countries with higher production productivity to the regions with less production productivity and reduces the water consumption in producing per unit of production (Chapagain et al. 2006). Trading the water-consumed products reduces the spatial heterogeneity of the access to water resources. Similarly, the domestic or
international trade improves the water use efficiency at the global or national scale by providing efficient products for all consumers (Dalin 2014).

Since the efficiency of agricultural water use, depending on the type of technology and biophysical factors, varies widely in different regions, the international or domestic food trade saves a significant amount of water resources globally or nationally if the regions with higher water resource efficiency export water to the less efficient regions (Chapagain et al. 2006). Measuring the international and domestic flow of water resources through the food trade contributes to the identification of the key exporters and importers and the performance evaluation of the trading system about the global water use (Dalin 2014).

The virtual water flows indicate the amount of virtual water exports and imports which are affected by various factors. Some of these factors such as population and gross domestic product (GDP) are considered in the country size group, and some other factors such as temperature, arable lands, and water resources inventory as natural resources affect the virtual water flows. The third group, known as the economic group, includes variables such as tariffs on agricultural products in the destination country, number of tractors in the destination country, amount of fertilizer consumed per hectare in the country of origin, and price of irrigation water. Each group of these variables affects the virtual water flows directly or indirectly (Fracasso et al. 2016). The predictions indicate that future food demand and supply change with the joint or independent impact of the climate change and population. Climate change limits global access to water and food production while increasing water consumption in all economic sectors (DaMatta et al. 2010; Strzepek & Boehlert 2010; Yawson et al. 2020). Furthermore, the population change directly and indirectly influences the global food and water supply and demand (Huang et al. 2010; Foresight 2011; Thomson et al. 2013).

The importance of virtual water flows has led to many studies in this area (Table 1), some of which have focused on quantifying the issue globally (Hoekstra & Hung 2002; Zimmer & Renault 2003; Islam et al. 2007; Lenzen et al. 2013; Biewald et al. 2014; Dalin 2014; Ercin & Hoekstra 2014; Verhoest et al. 2016), and of which some have examined the issue at the specific region (Wang et al. 2013; Zougides et al. 2014; Casolani et al. 2016; Deng et al. 2016; Zhu et al. 2016; Chouchane et al. 2018; Zhang et al. 2018). Factors affecting the virtual water flows and the future of the virtual water flows under different scenarios have been investigated in several studies (Fader et al. 2010; Pfister et al. 2011; Hanasaki et al. 2013; Konar et al. 2013; Liu et al. 2013; Ercin & Hoekstra 2014; Haddeland et al. 2014; Wada & Bierkens 2014; Zhu et al. 2015). Other studies examine the virtual water trade from an international perspective, considering water resources as well as water scarcity (Oki & Kanae 2004; Islam et al. 2007).

Generally, the situation is likely to become worse in the near future and it is reasonable to anticipate more competition for the water resources (United Nations 2015). In addition, based on the estimation on the national income growth provided by the World Bank (World Bank 2016) and the population growth by the World Population Prospect (United Nations 2019), it is predicted that the water demand for industrial activities and urban needs increases in the future. The significant increase in the water demand over the renewable domestic water resources, water scarcity, and its implications for food security have created major concerns in most of the countries (Ashktorab 2019).

Since Iran is heavily under water stress, it is necessary to consider all strategies mitigating the pressures on water resources by increasing water productivity and managing its demand. The present study examined the virtual water trading and adopted a clear strategy to use all the opportunities created and avoid the threats resulting from its application. Furthermore, it aimed to identify the determinants of bilateral virtual water flows associated with the international trade of the selected agricultural products such as wheat, barley, maize, rice, sugar beet, and tomato, which allocated 72% of the arable lands in Iran (Ashktorab 2019), and predict the size of the virtual water flows of the selected agricultural crops influenced by climate change and population scenarios in the future.

MATERIALS AND METHODS

Determinants of the virtual water flows in Iran

The idea of virtual water flows was originally proposed by Allan (1993, 1998) based on the economic concepts developed in the international trade literature, particularly in the Heckscher–Ohlin Vanek model (Fracasso et al. 2016). The results of numerous studies indicated that there are many variables playing a significant role in virtual water flows (Figure 1), which are divided into four groups, some of which are evaluated in the regional or global studies (Yang et al. 2003; De Fraiture et al. 2004; Ramirez-Vallejo & Rogers 2004; Yang & Zehnder 2007; Novo et al. 2009; Lenzen et al. 2012; Debaere 2014; Fracasso 2014).
The population and GDP of the exporting and importing countries are situated in the first group, and the population is expected to have a positive impact on the virtual water flows of the countries. The second group is related to the water inventory. Many studies indicated that the countries with inadequate water resources are net exporters of the virtual water (De Fraiture et al. 2004; Ramirez-Vallejo & Rogers 2004; Yang & Zehnder 2007; Verma et al. 2009; Roson & Sartori 2010, 2013). Among the variables related to the water inventory, four variables are considered for both exporting and importing countries. The first is the annual freshwater withdrawals for agricultural purposes. The second is related to the total green water demand under future climate change scenarios in the Loess Plateau of northern Shaanxi, China. The third is the total available water and the third variable is called the water availability ratio, which examines the pressure on the water resources and the agricultural lands of the exporting and importing countries are both considered as the factors influencing the virtual water flows (Fracasso et al. 2016). Some factors, such as production technologies, domestic and international prices of goods, trade barriers, and other economic and social characteristics, can affect the production, consumption, exchange of agricultural

| NO. | Title | Year | Size of virtual water flows | Determinants of virtual water flows | Climate change scenarios | Gravity model | Predicting the future |
|-----|-------|------|-----------------------------|-------------------------------------|--------------------------|--------------|----------------------|
| 1   | Virtual water flow in food trade system of two west African cities | 2019 | Yes                         | Yes                                 | No                       | No           | No                   |
| 2   | Drivers of virtual water flows on regional water scarcity in China | 2019 | No                          | Yes                                 | Yes                      | No           | Yes                  |
| 3   | Long term drivers of global virtual water trade: a trade gravity approach for 1965–2010 | 2019 | No                          | Yes                                 | Yes                      | Yes          | No                   |
| 4   | Water footprint of wheat under climate change: trends and uncertainties associated to the ensemble of crop model | 2019 | No                          | Yes                                 | Yes                      | Yes          | Yes                  |
| 5   | Global implication of regional grain production through virtual water trade | 2019 | Yes                         | Yes                                 | No                       | No           | Yes                  |
| 6   | Influential factors on water footprint: a focus on wheat production and consumption in virtual water import and export region | 2019 | Yes                         | Yes                                 | No                       | No           | Yes                  |
| 7   | Evaluation of agricultural water demand under future climate change scenarios in the Loess Plateau of northern Shaanxi, China | 2018 | No                          | Yes                                 | No                       | No           | Yes                  |
| 8   | Economic aspects of virtual water trade (Oki et al. 2017) | 2017 | Yes                         | Yes                                 | No                       | No           | Yes                  |
| 9   | Determinants of virtual water flows in the Mediterranean | 2016 | Yes                         | Yes                                 | No                       | No           | Yes                  |
| 10  | Modeling the future evolution of the virtual water trade network: A combination of network and gravity models | 2016 | Yes                         | Yes                                 | No                       | Yes          | Yes                  |
| 11  | Inter and intra-annual variation of water footprint of crops and blue water scarcity in the Yellow River Basin (1961–2009) | 2016 | Yes                         | Yes                                 | Yes                      | No           | Yes                  |
| 12  | Balancing water resource conservation and food security in China | 2015 | Yes                         | Yes                                 | No                       | Yes          | Yes                  |
| 13  | The global economics of water: Is water a source of comparative advantage? | 2014 | Yes                         | Yes                                 | No                       | Yes          | Yes                  |
| 14  | Water footprint scenarios for 2050: a global analysis | 2014 | Yes                         | Yes                                 | Yes                      | No           | Yes                  |
goods, and the water available in the agricultural products. The average tariff on the imported agricultural products, as one of the trade barriers for the agricultural goods importing country, affects the virtual water flows. Furthermore, the irrigation water costs should be considered as a determinant. However, the irrigation prices are distorted by agricultural policies and are usually kept artificially low, which directly affects the farmers’ decisions to produce (Wichelns 2004).

The productivity level of the agricultural sector influences the amount of virtual water flows. Some factors such as the number of tractors per 100 km² of arable land and kg of fertilizer consumed per hectare of arable land indicate the mechanization degree of a country and the level of agricultural productivity, as it is related to the agricultural sector (Fracasso et al. 2016). The education level of people in a country, based on the average number of years of education, reflects the level of socio-economic development and is considered as one of the factors influencing the virtual water flows (Barro & Lee 2013).

The model averaging method is used to select the determinants due to the high degree of uncertainty available in the empirical selection of the determinants of virtual water flows. The main features of the model averaging techniques are combining the model uncertainty with the analysis, averaging across all possible model characteristics, and identifying a set of possible explanatory variables by the researcher. Thus, the model averaging approach examines all possible sets of determinants instead of determining the correlation between the determinants based on one model or several pre-selected models. In the present study, the variables of population, GDP, average annual temperature, annual freshwater withdrawal for agriculture, arable land, and kg of fertilizer consumed per hectare were considered as the determinants of virtual water flows using model averaging. The gravity model was used to examine the factors affecting the virtual water flows of the selected crops and evaluate the export and import potential of these crops between Iran and other countries involved in importing or exporting these crops.
Evaluation of the gravity model

The empirical structure in this paper is based on a gravity model. The gravity model can accurately explain the bilateral trade flows. It is used for various purposes especially to assess market access, trade resistance, and impacts of regional and international agreements. The originality of the gravity model came back to Newton’s law of gravitation in the 17th century. The gravity model is a function of attraction factors such as ‘economic mass’ (GDP) and resistance factors such as distance ‘economic centers of gravity’, population and trade preference factors like a common language, common borders, and others which can affect international trade (Ashktorab & Shahnoushi 2013).

The gravity model is widely used by economists as one of the most useful tools in interpreting and explaining the trade flows among the countries around the world. The gravity model is often estimated for the sum of exports and imports. Here, the data were used to evaluate the effects of various variables on exporting and importing the selected agricultural products based on the gravity model. The process is modeled as follows:

\[
EX_{it} = e^{\alpha_i} \prod_{m} x_{imt}^{\beta_{mt}} \prod_{k} e^{\gamma_{kt}P_{ikt}} \epsilon_{it}
\]

(1)

Since the structure of the gravity model is based on the linear logarithm, the coefficients of this model are in terms of elasticities or percent ratios. Such evaluations are comparable across countries and goods and directly reflect the trade responses to the potential trade variables.

In the form of linear logarithm,

\[
\ln(EX_{it}) = \alpha_i + \sum_{m} \beta_{mt} \ln(x_{imt}) + \sum_{k} \gamma_{kt} P_{ikt} + \ln \epsilon_{it}
\]

(2)

where \(EX_{it}\) indicates the amount of virtual water flows of selected Iranian agricultural products to/from country \(i\) in year \(t\), \(x_{imt}\) demonstrates the \(m\)th explanatory variable for country \(i\) in year \(t\), \(P_{ikt}\) represents the \(k\)th variable, \(\epsilon_{it}\) displays the error term, and \(\alpha_i, \beta_{m}, \gamma_{k}\) illustrate the parameters which are estimated.

The explanatory variables of the model consisted of the determinants of virtual water flows such as population of each country, GDP of each country, annual average temperature, annual freshwater withdrawal for agriculture (% of the total freshwater withdrawal), arable land per hectare, fertilizer consumption (kg per hectare of the arable land), the geographical distance between the capitals of Iran and \(t\)th country (km) reflecting the transportation cost and the amount of information of the two business partners, the virtual variable of the existence of a common border, and a water frontier between Iran and its trading partners. Number 1 indicates its existence. Otherwise, the number is 0.

The gravity model for the virtual water flows of the selected agricultural products of Iran is as follows:

\[
\ln(EX_{it}) = \alpha_0 + \alpha_1 \ln(GDP_{it}) + \alpha_2 \ln(POP_{it}) + \alpha_3 \ln(AFW_{it})
+ \alpha_4 \ln(AL_{it}) + \alpha_5 \ln(FC_{it}) + \alpha_6 \ln(Dis_{it}) + \alpha_7 \text{border} + \ln \epsilon_{it}
\]

(3)

where \(EX_{it}\) displays the amount of virtual water flows of selected Iranian agricultural products to/from country \(i\) in year \(t\), \(GDP_{it}\) represents the GDP of country \(i\) in year \(t\), \(POP_{it}\) indicates the population of country \(i\) in year \(t\), \(AFW_{it}\) demonstrates the annual freshwater withdrawal for agricultural purposes of country \(i\) in year \(t\), \(AL_{it}\) illustrates the hectare of arable land in country \(i\) in year \(t\), \(FC_{it}\) displays the kg per hectare of fertilizer consumed in Iran in year \(t\), \(Dis_{it}\) represents the distance between Iran and countries importing/exporting the selected agricultural products, \(TEM_{it}\) demonstrates the average annual temperature in country \(i\) in year \(t\), border indicates the common border of Iran with the countries importing/exporting the selected agricultural products, and \(\epsilon_{it}\) indicates the error term.

The selected agricultural products include wheat, barley, maize, rice, sugar beet, and tomato, as each is separately exported and imported from/to different countries during 2000–2016.

Predicting future virtual water flows under the climate and population change scenarios

Global warming due to human activities and climate changes is considered as one of the issues which have attracted the attention of many experts and scientists in different sciences. The global climate change caused by rising greenhouse gas concentrations, especially carbon dioxide, is expected to cause changes in precipitation regime, wind speed, sunlight reaching the surface, and air temperatures. Rising temperatures and climate change have detrimental effects on water resources. The
climate change influences the water demand caused by rising temperatures and water supply (equilibrium in increasing carbon dioxide, evapotranspiration, and precipitation) (Hashempour et al. 2020). Therefore, adapting and coping with the climate change in the water resources sector along with their reduction reflection should be seriously considered as a part of the comprehensive response to the climate change-related vulnerability (Munang et al. 2013).

Currently, the most valid tool for generating climate change scenarios are the atmosphere-ocean coupled general circulation (AOGCM) 3D models (Wilby & Harris 2006), which use the periodic mean of AOGCM data in the climate change calculations. The early studies indicated that the best statistical period is 30 years. Based on the World Meteorological Organization (WMO), the base period of 1961–1990 is considered to coordinate and compare the base period selection in the different climate change studies. Furthermore, the WMO recommended to replace the period 1971–2000 when the data recorded at the stations of the studied area are not available for this period (IPCC-TGCIA 1999). Therefore, given the inventory of the climate variable statistics of the studied stations, the period of 1971–2000 was selected as the base period and the periods of 2016–2045 and 2070–2099 as the future periods.

The present study used the results of the study of Delghandi & Moazenzadeh (2017) as the output analysis of 15 models of HadCM3, CHAM5/MPI-OM, CSIRO-MK3.5, GFDL-CM2.0, CNRM-CM3, CGCM3 (T63), GISS-R, MRI-CGM2.5.2a, IPSL-CM4, CHO-G, BCM2.0 and MIROC3.2 mdr, INMCM3.0, NCAR-CCSM3, and NCARPCM were used, which simulates the climate data under the A2, A1B, and B1 emission scenarios, indicating the most critical, average, and lowest rate of greenhouse gas emissions, respectively.

The results of their study indicated that the temperature changes in the first (2016–2045) and second future periods (2070–2099) compared to that in the previous period were calculated for Iran under the A2, A1B, and B1 emission scenarios using the existing equations. The middle number assigned to each period (2025 and 2085) was used to indicate the future period.

In the first future period, the three emission scenarios predicted the same temperature rise of about 1.5. However, it is different for the second future period when the pessimistic scenario of A2 and the optimistic scenario of B1 predicted the highest and lowest temperature increase, respectively. Furthermore, the A1B scenario is the intermediate of these two scenarios. In the second future period and under the A2 scenario, the temperature rises about 5 °C, since such temperature rises makes life difficult in the tropical regions of Iran, especially in the cities located in the margin of the Persian Gulf. The temperature rise is about 2.5 °C under the B1 scenario and about 4 °C under the A1B scenario (Delghandi & Moazenzadeh 2017).

In addition, the population of Iran as a determinant of the virtual water flows has been increasing over time. The average annual population growth in the middle period of 2016–2045) and second future periods (2070–2099) is considered to coordinate and compare the base period selection in the different climate change studies. Furthermore, the WMO recommended to replace the period 1971–2000 when the data recorded at the stations of the studied area are not available for this period (IPCC-TGCIA 1999). Therefore, given the inventory of the climate variable statistics of the studied stations, the period of 1971–2000 was selected as the base period and the periods of 2016–2045 and 2070–2099 as the future periods.

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In addition, the population of Iran as a determinant of the virtual water flows has been increasing over time. The average annual population growth is predicted by Statistical Center of Iran (2018). Based on the results, the average population growth is 0.98% for 2025 and 0.44% for 2085. Considering the average population growth of Iran in 2025 and 2085 as well as various emission scenarios, the net variations of the virtual water flows were calculated.

The data required for 2000–2016 such as population of each country, GDP of each country, annual freshwater withdrawal for agriculture (% of the total freshwater withdrawal), arable land (hectare), and fertilizer consumption (kg per hectare of arable land) were collected from the World Bank website. To provide the export/import volume of the selected products, destinations and the volume of export and import of each product were first identified from the website of the Food and Agriculture Organization of the United Nations (FAO). The water footprint of the selected products in Iran, calculated by Ashktorab (2019), was then used and multiplied by the amount of the export/import of the intended product to calculate the virtual water flows of each product. The average annual temperature of each country was obtained from the website of the National Centers for Environmental Information. The Internet software of city distance tool was used to determine the geographical distance between Iran and the capital of other countries. Accordingly, the geographical distance (km) of Tehran as the capital of Iran and the capital of the country importing/exporting the selected products was obtained, indicating the distance between these two countries.

Data
Population, GDP, annual freshwater withdrawal for agricultural purposes (% of the total freshwater withdrawal), arable land (hectare), and fertilizer consumption (kg per hectare of arable land) data for 2000–2016 were collected from the World Bank website. To provide the quantity of virtual water exports of six selected products, the destinations and the quantity of exports were identified from the Food and Agriculture Organization of the United Nations website, and the average annual temperature of each country was obtained from National Centers for Environmental Information. The average water footprint (Ashktorab 2019) of each product was used to calculate the virtual water flows.
RESULTS AND DISCUSSION

Given the equations, the results of tests, calculations, regression, and model prediction are presented, and based on the results, the final analysis and interpretation are performed.

Results of poolability test

The $F$-test was calculated separately for the cross-sections and time series. The obtained statistical value was 593.43. Based on the statistical value in the $F$-statistic table, $H_0$ was rejected and the group effects were accepted. Therefore, the usability of the panel data method was confirmed.

The value of $F$-statistic for the period 2000–2016 was 742.12 and given the statistical value existing in the $F$-statistic table, $H_0$ was rejected and applying the panel data method was confirmed.

Results of panel unit root test

The stationarity of the variables should first be examined in estimating the panel data models like the time-series models, and the effects of the random process are eliminated from the data if necessary. Given the already mentioned statistics, Table 2 indicates the panel unit root test results of the variables.

As shown in Table 2, all the variables reject the null hypothesis of the unit root in their levels by test: the Levin, Lin, and Chu tests. This finding indicates that all the variables are stationary.

Result of the Hausman test

The Hausman test statistic is equal to 10.56. Due to the calculated statistic, the $H_0$, indicating the lack of correlation between individual effects and $X_{it}$, was rejected. Based on the results, the rejected random effects and the fixed effects are significant.

Results of the gravity model estimation with the panel data method

The net virtual water flows of the selected Iranian products were calculated based on each business partner during 2000–2016 (Figure 2).

The results indicated that Iran had the highest amount of virtual water imports for the selected products from Brazil, as well as the lowest amount of virtual water imports from Turkey during 2000–2016. Australia, South Africa, and Canada ranked the second to fourth as the highest exporters. The results revealed that most imports of the selected products and the virtual water were from long-distance countries and neighboring countries of Iran played a slight role in exporting these products to Iran during the 17-year period. Therefore, it is predicted that the distance variable, as a virtual water flow determinant, cannot have a significant effect on the virtual water flows of the selected products.

Table 2 | Results of panel unit root test

| Variables                        | Levin–Lin & Chau test |
|----------------------------------|-----------------------|
| ln(EX$_{it}$)                    | -5.88 (0.00)          |
| ln(GDP$_{other,t}$)              | -4.78 (0.00)          |
| ln(GDP$_{Iran,t}$)               | -7.52 (0.00)          |
| ln(POP$_{Iran,t}$)               | -5.59 (0.00)          |
| ln(POP$_{other,t}$)              | -4.36 (0.00)          |
| ln(AL$_{other,t}$)               | -13.88 (0.00)         |
| ln(AL$_{Iran,t}$)                | -1.58 (0.05)          |
| ln(FC$_{Iran}$)                  | -2.96 (0.00)          |
| ln(AFW$_{other,t}$)              | -2.84 (0.00)          |
| ln(AFW$_{Iran,t}$)               | -1.74 (0.00)          |
| ln(Dis$_{ij}$)                   | -7.01 (0.00)          |
| ln(TEM$_{other,t}$)              | -4.21 (0.00)          |
| ln(TEM$_{iran,t}$)               | -3.36 (0.00)          |

Note: The value in parenthesis indicates the significance at 1% level with respect to the rejection of the null of nonstationary.
Table 3 demonstrates the model estimation results to examine the effect of the determinants of the virtual water flows through the trade of the selected products using the panel data method.

The GDP of Iran and its trading partners was considered to estimate the gravity model of virtual water flows of selected products of Iran. An increase in the income and production of each country leads to an increase in its demand for imports of goods and services from the opposite country. Therefore, the coefficient of these variables is positive in the model. Table 3 indicates that the GDP of Iran is positive. In constant conditions, a 1% increase in the GDP of Iran enhances the virtual water flows of selected products by 0.29%. Since Iran is a net importer of the selected products (Ashktorab 2019), this coefficient demonstrates an increase of 29% in imports of these products. Based on the data obtained from the Food & Agriculture

| **Table 3 | Determinants of virtual water flows of selected agricultural products in Iran** |
|---------|----------------------------------|-----------------|-------------|
| Variables | Coefficients | t-statistic | Prob.        |
| C       | −4.38        | −14.49       | 0.08        |
| Population (Iran) | 0.25 | 1.72 | 0.02        |
| Population (partners) | −0.06 | −3.03 | 0.09        |
| GDP (Iran) | 0.29 | 3.61 | 0.00        |
| GDP (partners) | 1.35 | 0.95 | 0.79        |
| Arable land (Iran) | −0.36 | −1.01 | 0.54        |
| Arable land (partners) | 0.12 | 3.49 | 0.00        |
| Fertilizer consumption (Iran) | 0.03 | 1.79 | 0.03        |
| Annual freshwater withdrawal (Iran) | 0.15 | 2.27 | 0.00        |
| Annual freshwater withdrawal (partners) | −0.07 | −1.61 | 0.01        |
| Annual average temperature (partners) | −0.17 | −1.26 | 0.82        |
| Annual average temperature (Iran) | 0.11 | 2.21 | 0.02        |
| Distance | −0.79 | −1.04 | 0.52        |
| Common border | 0.43 | 1.58 | 0.04        |
| R²      | 0.86        | F-statistic  | 226.37      |
| R       | 0.75        | Durbin–Watson statistic | 2.06        |
Organization (2016), Iran is a net importer of wheat, barley, maize, and rice and, consequently, a net importer of virtual water through these products. Given that these products have a significant share in the food pattern of Iran and wheat is a strategic product, the purpose of its production is self-sufficiency. Furthermore, the products such as rice and maize require a high amount of water. Considering the water resources status in Iran, the aim is to reduce their consumption. Therefore, the imports of these products enhance by increasing the GDP, and consequently, the virtual water imports increase through these products. On the other hand, it can be said that the economic growth caused by the increase in GDP leads the country to focus more on industrialization and shrink the agricultural sector (Figure 3). This factor causes a decrease in the export of agricultural products, which leads to a decrease in the export of virtual water, and in order to feed the population, the import of agricultural products, as well as the import of virtual water increase, while the time trend of this issue depends on the preferred policies of each country.

In this model, the population was separately determined for Iran and the countries importing/exporting selected products. It is predicted that the importing country with larger population imports more to meet their needs. However, the effect of the population increase in the exporting country on the imports of the importing country is unclear. Therefore, the coefficient of this variable seems positive for the population of the importing country, while this coefficient for the population of the exporting country is uncertain. As shown in Table 3, the population of Iran and the trading partners of the selected products were significant in the present study. The positive sign of the population of Iran indicates that the imports of these products increase when the population of Iran increases (Figure 4). Since the selected agricultural products are considered as the basic products in the food pattern of Iran, the population growth results in increasing the demand for these products, and accordingly the imports due to the reduction of the water resources. On the other hand, the exporting countries with a larger population are less inclined to the bilateral trade and focus more on domestic consumption. Furthermore, the results indicated that a 1% increase in the population leads to a 0.25% increase in the virtual water trade of the selected agricultural products in Iran. However, a 1% increase in the population of trading partners of Iran leads to a 0.06% reduction in the trade of the selected crops.

In the present study, the physical distance between countries is considered as a substitution for the transportation costs. Since the transportation costs have a negative impact on the trade between countries, the distance is negative based on the theory and has no significant effect on virtual water flows (Table 3). Given that the commercial targets of the selected crops are mainly in Europe and sometimes in Australia and Canada, the comparative advantage principle in relation to the crop production and the production technology leads to the reduction of the production costs and the final product prices, which covers the transportation costs. Therefore, Iran imports a greater share of its required selected crops from the countries with high physical distance (Figure 2). The common boundary is entered into the model as a virtual variable. In the present study, the countries with a common water or soil boundary with Iran are numbered 1 and the other countries as 0. Furthermore, the common border has a significant effect on the virtual water flows of the selected crops. Iran imports a
limited number of selected crops from neighboring countries and exports some of these crops to them. Arable land, fertilizer consumption, and annual freshwater withdrawal for agriculture affect virtual water flows. The arable land refers to the lands used for agriculture. This variable has a positive coefficient for exporting countries and a negative coefficient for importing countries. Table 3 demonstrates a negative coefficient for Iran, the net importer of selected agricultural products, which is not significant. Given that the water resources have declined dramatically in Iran in recent years, it is not possible to increase the production and reduce the imports of selected crops in Iran only by increasing the cultivation area. The low productivity of the arable land in Iran is related to the salinity, gravel, soil density, and lack of organic resources, impeding production. The coefficient of an arable land variable is positive and significant for trading partners of Iran, which indicates that the trading partners of Iran increase the production of the desired crops by increasing cultivated lands, leading to an increase in the exports of these crops and virtual water. There are several variables indicating the pressure on the water resources (Fracasso et al. 2016). In the same vein, the annual freshwater withdrawal variable for agriculture is considered as one of the variables demonstrating the pressure on the renewable water resources. The virtual water trade decreases in the countries with high water resources withdrawal. Therefore, this variable has a negative coefficient for the countries exporting the virtual water and a positive coefficient for the virtual water importing countries.

As shown in Table 3, the annual freshwater withdrawal variable for agriculture in Iran is positive and significant, indicating that the pressure on the renewable water resources in Iran decreases by increasing the virtual water trade. This coefficient is negative and significant for the trading partners in Iran, which demonstrates that the export of agricultural products increases the pressure on the water resources of those countries. A 1% increase in the annual freshwater withdrawal for agriculture enhances the virtual water imports of Iran by 0.15% due to the increased water withdrawal costs and reduces the virtual water exports of trading partners by 0.07%, since an increase in groundwater utilization leads to irreparable damages to the groundwater resources. The excessive withdrawal of groundwater resources increases the saline aquifers, as well as the salinity in the freshwater resources in different regions of the world. The level of underground aquifers has decreased in Iran over the past decades due to the continuation of low precipitation compared to the long-term trend and the improper utilization of water resources, especially in the agriculture (Karimi et al. 2018). In this regard, the virtual water imports reduce the pressures on the water resources.

Fracasso et al. (2016) considered the fertilizer consumed per hectare of arable land as a measure of the mechanization of a country. This variable is intended only for the country of origin, which positively affects the virtual water flows, which has a positive relationship with the production technology. Based on the results in Table 3, the coefficient of this variable is positive and significant, demonstrating that the enhancement of the fertilizer consumed per hectare results in increasing the production, as well as the exports of agricultural products and virtual water. Although the use of agricultural fertilizers increases the gray water footprint, their impact on increasing production cannot be ignored. Furthermore, the changes in the fertilizer consumed per hectare in Iran alter the virtual water flows of the selected crops by 5%. Based on the average annual temperature, the temperature and heat enhancement increase the evapotranspiration and the water requirement of the plant and, subsequently, alter the water footprint of the plant and the virtual water flows. The positive coefficient of
this variable for Iran demonstrates that the net virtual water flows enhance by increasing the average annual temperature. Furthermore, a 1% increase in the average annual temperature enhances the virtual water imports of Iran by 0.11%, due to the increased evapotranspiration at the farm level. The coefficient of this variable is insignificant for other countries (Table 3).

Figure 5 demonstrates the net virtual water flows of the selected products separately. The net virtual water flows of wheat, barley, maize, and rice have the highest value during 2000–2016 (Figure 5). The average population growth in Iran in the 10-year period before 2014 increased more than that in the other periods (Statistical Center of Iran 2018). Therefore, the population growth leads to a net increase in the imports of selected crops to meet the demands of the growing population. In addition to population changes, an increase in rainfall in some years has led to an increase in green water footprint, and also in some years, a decrease in rainfall has led to a decrease in green water footprint. Changes in water footprint have led to fluctuations in net virtual water flows.

**Future virtual water flows under different scenarios**

Future virtual water flows under climate change scenarios

The present study predicted the size of the virtual water flows in the future based on the findings of Delghandi & Moazenzadeh (2017), in relation to the average annual temperature change in the coming years under the A2, A1B, and B1 emission scenarios, indicating the most critical, average, and lowest greenhouse gas emissions, respectively.

The determinants of virtual water flows were identified during 2000–2016. The average annual temperature as a determinant of virtual water flows has a positive and significant effect on the net virtual water flows of selected crops in Iran (Table 3). The other variables were considered constant, and the changes were applied to the average annual temperature in Iran to predict the changes in the virtual water flows in the future (Table 4).

In the first future period (2016–2045), the average annual temperature under three climate change scenarios increases by 1.5 °C, leading to a change of 6.1 milliard cubic meters in net virtual water flows. Given that an average of 37 milliard cubic meters of virtual water was imported through importing the selected products during 2000–2016 (Ashktorab 2019), this

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**Figure 5** | Net virtual water flows of selected products (2000–2016).

**Table 4** | Predicting virtual water flow changes under climate change scenarios

| Climate change scenarios | A2  | B1  | A1B |
|--------------------------|-----|-----|-----|
| Net virtual water flow changes in the first future period (milliard cubic meters) | 6.1 | 6.1 | 6.1 |
| Net virtual water flow changes in the second future period (milliard cubic meters) | 20.33 | 10.16 | 16.26 |
amount increased by 6.1 milliard cubic meters in the first future period due to the positive effect of the change in the average annual temperature on the virtual water flows (Table 4).

In the second future period (2070–2099), the average annual temperature under scenario A2 (pessimistic) increases by 5 °C, leading to an increase of 20.33 milliard cubic meters of the virtual water imports through importing the selected products. In the scenario B1 (optimistic), a 2.5 °C increase in the average annual temperature enhances 10.16 milliard cubic meters of virtual water flows. Furthermore, a 4 °C increase in the temperature in the scenario A1B results in increasing 16.26 milliard cubic meters in the net virtual water flows in the second future period (Table 4).

**Future virtual water flows under the population change scenarios**

In this section, the virtual water flows in the future under the population change scenarios were predicted. The average annual population growth of Iran for 2025 and 2085 is calculated 0.98 and 0.44%, respectively.

The average population of Iran, as a determinant of virtual water flows, has a positive and significant effect on the net virtual water flows of the selected crops in Iran (Table 3). To predict changes in the future virtual water flows, other variables were considered constant, and the changes were applied to the average population of Iran (Table 5).

In the first future period (2016–2045), the average population growth is 0.98%, which leads to a change of 9.1 milliard cubic meters in net virtual water flows. Considering that an average of 37 milliard cubic meters of the virtual water was imported through importing the selected products during 2000–2016, this amount increased to 9.1 milliard cubic meters in the first period due to the positive effect of changing the average annual temperature and the population of Iran on the virtual water flows (Table 5). In the second future period (2070–2099), the average population growth is 0.44%, leading to an increase of 4.07 milliard cubic meters of virtual water imports through importing the selected products (Table 5).

**Future virtual water flows under the climate and population change scenarios**

The virtual water flows in the future under the climate and population change scenarios were predicted here. The average annual temperature and the population of Iran, as the determinants of virtual water flows, have a positive and significant effect on the net virtual water flows of the selected crops in Iran (Table 3). The average annual temperature and the population of Iran were changed, and other variables were considered constant to predict changes in the future virtual water flows (Table 6).

In the first future period (2016–2045), the average annual temperature under all three climate change scenarios increases by 1.5 °C and the average population growth is 0.98%, leading to a change of 15.17 milliard cubic meters in the net virtual water flow (Table 6).

In the second period (2070–2099), the average annual temperature under scenario A2 (pessimistic) increases by 5 °C and the average population growth is 0.44%, leading to an increase of 24.42 milliard cubic meters of virtual water imports by

**Table 5 | Predicting virtual water flow changes under population change scenarios**

| Population change scenarios | Net virtual water flow changes in the first future period (milliard cubic meters) | Net virtual water flow changes in the second future period (milliard cubic meters) |
|-----------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| A2                          | 9.1                                                                              | 4.07                                                                            |

**Table 6 | Predicting virtual water flow changes under climate and population change scenarios**

| Population change scenarios | Climate change scenarios |
|-----------------------------|-------------------------|
| A2                          | B1                      |
| The average population growth is 0.98% | 15.17 15.17 15.17 |
| The average population growth is 0.44% | 24.42 14.25 20.35 |
importing the selected products. In the scenario B1 (optimistic), an increase of 2.5 °C in the average annual temperature and the average population growth of 0.44% leads to an increase of 14.25 milliard cubic meters of the net virtual water flows. Furthermore, in the A1B scenario, an increase of 4 °C, along with an average population growth of 0.44%, increases the temperature to 20.35 milliard cubic meters of the net virtual water flows in the second future period (Table 6).

Based on the results, the temperature and population variation in the future change the amount of the virtual water flows. Therefore, the imports of agricultural products increase in future periods to meet the food demand of the population, leading to the increased virtual water imports.

CONCLUSION

Given that agriculture is considered as the largest consumer of water resources in the world, the management of the virtual water trade is proposed as a policy for food supply, protection, and sustainability of water resources, as well as a strategy for the storage of water resources of each country, and achieving water security at the national level. In the present study, the determinants of virtual water flows were identified and their influence was examined using the gravity model. Furthermore, the size of the future virtual water flows was predicted under the climate and population change scenarios. The results indicated that the factors such as the populations of countries having trade flows (exports and imports) together, GDP, annual freshwater withdrawal for agriculture (% of the total freshwater withdrawal), arable land in hectare, fertilizer consumption in kg per hectares of arable land, the distance between countries, and the common border are the determinants of virtual water flows in Iran. Based on the results of the Food and Agriculture Organization (2016), Iran is a net importer of wheat, barley, maize, and rice and, consequently, a net importer of virtual water through these products. Given that the water resources in Iran have declined dramatically in recent years, the production cannot be increased and the imports of the selected agricultural products cannot be reduced in Iran only by increasing the cultivation area.

The early domestic studies, which examined temperature changes under the climate change scenarios, were used to predict the size of the virtual water flows of Iran in the future. The results indicated that the average annual temperature under all three climate change scenarios increase by 1.5 °C in the first future period (2016–2045), which can lead to a change of 6.1 milliard cubic meters in the net virtual water flow. In the second future period (2070–2099), the average annual temperature under the pessimistic, optimistic, and intermediate scenarios can increase by 5, 2.5, and 4 °C, respectively, leading to an increase of 20.33, 10.16, and 16.26 milliard cubic meters of virtual water imports through the import of the selected products. Furthermore, the climate change scenarios, along with the average population change, were examined in both future periods. The average population growth in the first and second future periods was 0.98 and 0.44%, respectively. The results indicated that the net virtual water flows increase by 9.44 milliard cubic meters in the first future period. In addition, the net virtual water flows increase by 21.82, 11.64, and 17.75 milliard cubic meters, respectively, in the second future period under the three pessimistic, optimistic, and intermediate scenarios.

By considering the above-mentioned issues, as well as the political conditions prevailing in the country, the following recommendations are suggested:

1. Increasing the virtual water flows through the imports of the agricultural products with high water footprint results in increasing the share of flows to the irrigation water in the agricultural sector and decreasing the pressure on the water resources of Iran. Therefore, it is recommended to change the trade policies fundamentally based on the enhancement of the virtual water imports.

2. The results indicated that the agricultural products are mainly imported from countries with a long geographical distance from Iran. Therefore, it is suggested to decrease the import tariff of agricultural products with high water footprint and increase the export tariff of agricultural products with high water footprint to increase the virtual water imports. On the other hand, finding similar products from nearby or neighboring countries that have a lower water footprint is also a real possibility in virtual water trading.

3. The government can use an ad valorem import and export tariff policy depending on the amount of each product’s water footprint so that products with more water footprint apply higher export tariffs as well as lower import tariffs.

4. The government can use export quotas according to the water footprint, which could lead to a reduction in the area under cultivation of water-intensive crops.
5. The results of the simulation scenario of population and temperature enhancement demonstrated an increase in the virtual water imports into Iran. Therefore, it is necessary to identify countries with the lowest import costs and adopt appropriate trade policies as soon as possible.

6. The food supply for future generations is considered as one of the problems facing policymakers due to the water resources constraints. Given the political relations of Iran with other countries, the population reduction policies should be considered over a specific period.

7. Considering that the dominant food pattern in Iran includes rice as a water-consuming product, changing the present food pattern significantly reduces the pressure on the water resources, as well as the dependence on imports of this product.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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