Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-398
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 September 2018

Hydrology and Earth System Sciences
Discussions

Assessment of food trade impacts on water, food, and land security in the MENA region

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Abstract

The Middle East and North Africa (MENA) region has the largest water deficit in the world. It also has the least food self-sufficiency. Increasing food imports and decreasing domestic food production can contribute to water savings and hence to increased water security. However, increased domestic food production is a better way to achieve food security, even if irrigation demands increase in accordance to projected climate changes. Accordingly, the trade-off between food security and the savings of water and land through food trade is considered as a significant factor for resource management, especially in the MENA. Therefore, the aim of this study is to analyze the impact of food trade on food security and water-land savings in the MENA region. We concluded that the MENA region saved significant amounts of national water and land based on the import of four major crops, namely, barley, maize, rice, and wheat, within the period from 2000 to 2012, even if the food self-sufficiency is still at a low level. For example, Egypt imported 8.3 million ton/year of wheat that led to 7.5 billion m³ of irrigation water and 1.3 million ha of land savings. In addition, we estimated the virtual water trade (VWT) that refers to the trade of water embedded in food products and analyzed the structure of VWT in the MENA region using degree and eigenvector centralities. The study revealed that the MENA region focused more on increasing the volume of virtual water imported during the period 2006–2012, yet little attention was paid on the expansion of connections with country exporters based on the VWT network analysis.

Keyword: *Food security; Food self-sufficiency; Food trade; Virtual water; MEAN.*

1 Introduction

Primary resource gaps for the MENA region in terms of safe and affordable access to water, food, energy, and nutrition, are expected to grow owing to demographic, population, and climate changes. These primary resources are highly interlinked and create a high-degree of risks and vulnerability. The food portfolio in the MENA region has been complicated by an increased degree of risks owing to the geopolitical challenges and inability to satisfy needs with domestic production. This is in part due to lack of adequate arable land and water resources. As such, trade has been a major part of the food security portfolio, and has created another level of complexity that has been understudied.

The VWT refers to the trade of water embedded in food products (Allan, 1993; Aldaya et al., 2010; Antonelli and Tamea, 2015). Therefore, food trade drives water conservation or loss in terms of VWT, and it is an important element of both food and water security in water-scarce regions (Konar et al., 2012; Hanjra and Qureshi, 2010; Hoekstra, 2003). The concept and quantitative estimates of virtual water can help to realistically assess water scarcity for each country, projecting future water demand for food supply, thus increasing public awareness on water and identifying water-wasting processes in production (Oki and Kanae, 2004). For water-scarce countries, achieving water security by importing water intensive products could be a more attractive option compared to producing all water-demanding products domestically (Hoekstra and Hung, 2005). The global volume of international crop-related virtual water flows averaged 695 billion m³/year over the period 1995–1999, which means that 13% of the water used for crop production in the world was not used for domestic consumption but rather for export in virtual forms (Hoekstra and Hung, 2005). Falkenmark and Lannerstad (2010) estimated that it would be necessary to double the VWT by 2050 to compensate for agricultural water deficits because of climatic change, population increase, and the pattern of food supply per capita. For example, an average of 20% of the per capita food energy supply was assumed to originate from animal foods to ensure sufficient protein content, and additional water was required to produce animal foods compared to other food types (Falkenmark and Lannerstad, 2010).

The VWT could contribute to the relief of water stress through the use of global water in a more efficient manner in the event of an increase in the global food trade (Molden, 2007). Additionally, the VWT and the respective savings garnered through the trade of agricultural goods have been quantified in a number of studies. Oki and Kanae (2004) investigated that approximately 1140 km³/year of virtual water could be used for altering the import of food products to domestic products, e.g., cereals, soybeans, and meat; however, 680 km³/year of water was used to produce these food types in exporting areas. Yang et al. (2006) revealed that the VWT could generate global water savings because virtual water has flown primarily from countries of increased crop water productivity to countries of low-crop water productivity. In their study, 336.8 km³/year of water were saved globally by the international trade of major food crops from 1997 to 2001, while 20.4% of the total global net virtual water import was imported by countries that have water availability below 1700 m³ per capita, such as the Arab countries. Fader et al. (2011) calculated the VWT based on the trade of crop products, and compared it with the water requirements for producing crop products in each country for domestic consumption without international trade. Generally, exporters use less water for production of crop products than importers. Thus, the trade of crop products saves 263 km³/year of water globally, thereby representing 3.5% of the annual precipitation on cropland (Fader et al., 2011). In particular, water-scarce countries, such as China and Mexico, as well as Netherlands and Japan, saved large amounts of water by importing goods that require water in the range from 25 to 73 km³/year, because they would otherwise need relatively large amounts of water to produce the goods they import. According to the study by Biewald et al. (2014), blue water, which refers to the irrigation water supplied from artificial facilities, such as reservoirs, ground water pumping or desalination stations, was saved in importing countries by importing products in accordance to international trade. It is expected that this can elicit enormous benefits in water-scarce regions. For example, 17 billion m³ of blue water per year were saved by the global food trade, and the value of blue water saving was estimated to 2.4 billion US$.

Previous studies showed that the effective import of virtual water may reduce water use for domestic food production in importing countries and help alleviate water stress in the MENA region where the largest water deficit in the world exists (Gleick, 2000; World Bank, 2009). The critical condition of water scarcity in the MENA region will reach severe levels by 2025 (Tolba, 2009). In addition, if population increases rapidly and urbanization continues fast, availability of water could be reduced in the Arab countries by approximately 50% by the year 2025 (Abahussain et al., 2002). Water shortages will certainly speed up the rate of desertification in the Arab countries with a larger deficit in freshwater (Abahussain et al., 2002). Agricultural water withdrawals account for over 85% of the total water withdrawn by the various countries of the MENA region (FAO, 2014). Irrigation systems in the MENA region are based on pumping groundwater resources, such as aquifers, and water security is being threatened by the declining aquifer levels and the extraction of nonrenewable groundwater (Antonelli and Tamea, 2015). In addition, Immerzeel et al. (2011) expected that the unfulfilled water demand in the entire MENA region would increase from the current level of 16% to 51% in 2040–2050 owing to climate changes. The zone of severely reduced rainfall extends throughout the Mediterranean region and the Northern Sahara (Hennessy et al., 2007). Milly et al. (2005) identified that climate change will cause a decrease in water run-off by 20% to 30% in most of the MENA region by 2050, mainly owing to the rising temperatures and lower precipitation. In addition, the regions that include Syria, Lebanon, Israel, and Jordan, will get drier, with significant rainfall decreases in the wet season.

However, the high dependency on food import can be a risk of food security, even if it can elicit domestic water, energy, and land savings, in water-scarce regions. Therefore, we should consider a trade-off between food security and resource savings, using a holistic approach, such as water–energy–food nexus. Furthermore, the VWT can be suggested as relevant to the water policy of a nation (Schyns and Hoekstra, 2014), thus establishing a new point-of-view from which both food security and sustainable water management are considered (Novo et al., 2009).

This study addresses three questions that relate to the role and impact of the VWT in the MENA region, that are raised to draw attention to the complexity of the issue and the need for a broader view in assessment. Specifically, 1) what are the effects of the VWT on water savings and land tenure in the MENA region, 2) has the structure of the virtual water import in the MENA region been vulnerable or robust? 3) Who are the influential importers and exporters in the VWT network in the MENA region?

The aim of this study is to evaluate the effects on water savings and land tenure from importing crops in the MENA region. In addition, we quantified the amount of VWT from 2000 to 2012, and analyzed a structure of the VWT, such as the connectivity and influence in the MENA region using degree and eigenvector centralities.

2 Materials and Methods

2.1 National water and land savings in importing countries using footprints

The import of crops in the MENA region could affect the domestic resource management in terms of resource saving. Water saving indicates the amount of water needed to produce the same quantity of imported crops but as a domestic production. Accordingly, the failure of trade could cause water and land shortages in the importing country. Although this assumption about water and land savings considers an extreme trade situation, these results could be used to understand the importance of the international crop trade in the MENA region.

In this study, the national water and land savings indicated the amount of water and land requirements for crops imported to substitute domestic production. Therefore, we applied the water and land footprints to calculate water and land savings. The water footprint of a crop indicates the total amount of water used for producing 1 ton of crop, and land footprint indicates the land requirement for producing 1 ton of crop. The national water and land savings were calculated as follows,

$$WFP\ [n_i, c] = \frac{CWR\ [n_i,c]}{P\ [n_i,c]} \tag{1}$$

$$LFP[n_i, c] = \frac{Area\ [n_i,c]}{P\ [n_i,c]} \tag{2}$$

$$WS\ [n_i, c] = CI\ [n_i, c] \times WFP\ [n_i, c], \tag{3}$$

$$LS\ [n_i, c] = CI\ [n_i, c] \times LWP\ [n_i, c] \tag{4}$$

in which variable WFP $[\mathrm{n_i}, \mathrm{c}]$ (m³/ton) is the water footprint of crop c in the importing country n_i, CWR is the crop water requirement (m³), and P is the production (ton). Equivalently, LFP$[\mathrm{n_i}, \mathrm{c}]$ (ha/ton) is the land footprint of crop c in the importing country n_i, and $Area$ is the cultivated area (ha). The symbol WS (or LS) indicates the amount of water (or land) savings in the importing country n_i. CI is the import of crop c in the importing country n_i.

The water footprint of crops is based on crop water requirements and irrigation. Therefore, various datasets are required for calculating it, such as climate data, crop information, irrigation scheduling, and soil characteristics. In addition, each variable is dependent on local characteristics. In addition, the water footprint for a crop is divided into green and blue water footprints based on the water resources (Hoekstra and Chapagain, 2008). The green water footprint indicates that water supplied by precipitation is retained in the soil of the root zone (Falkenmark, 1995), and blue water footprint is the water stored at the surface or in the ground. Therefore, the green water footprint is related to rain-fed agriculture and the blue water footprint is related to irrigation water provided by aquifers or surface bodies of water. As the water footprint is divided into green and blue water footprints, the water saving could be considered as green and blue water saving as well. Thus, the study for national water footprint should be executed for each country, basin, or specific area; however, this was outside the scope of the current study.

In this study, the estimation of the water footprint was not included but we applied national water footprint data of countries from the study executed by Mekonnen and Hoekstra (2010). They estimated the average value of green and blue water footprints of crops and crop products at the national level from 1996 to 2005, as shown in Table 1. However, the data of the water footprint in the MENA region was limited in terms of availability. For example, Table 1 shows that the water footprint of wheat was available in all countries except for Bahrain. Therefore, we applied the limited water footprint in this study. The land footprint was calculated based on the harvest area and crop production, which were collected from FAOSTAT, as shown in Table 2.

Table 1. Water and lands footprints of four major crops in the MENA region

Table 2. Cultivation area, production, and the quantity of crops imported in the MENA region from 2000 to 2012

2.2 VWT based on international trade

The VWT represents the water embedded in international trade, and it indicates the water used in the exporting country to produce crops for export. For example, Saudi Arabia imported wheat from various exporters, and the VWT was calculated by multiplying the quantity of traded wheat with the respective water footprint of exporters. In other words, the VWT is calculated based on the water footprint of exporters. Thus, the export of virtual water in the exporting country has the same meaning as the import of virtual water has in the importing country. Accordingly, the main factors for quantifying a VWT are the trade data and water footprint, and the VWT is calculated by multiplying the trade by its associated water footprint in the exporting country, as follows:

$$VWT\ [n_e, n_i, c, t] = CT\ [n_e, n_i, c, t] \times WFP\ [n_e, c], \tag{5}$$

where the variable VWT denotes the virtual water trade from the exporting country, n_e, to the importing country, n_i, in year t, as a result of trade in crop c, CT represents the crop trade from the exporting country, n_e, to the importing country, n_i, in year t as a result of trade in crop c, and WFP represents the water footprint of crop c in the exporting country, n_e.

The international trade data of the four major crops, namely, barley, maize, rice, and wheat from 2000 to 2012 was obtained from FAOSTAT (http://www.fao.org/faostat/), as shown in Table 2. The crop with the largest amount of import was wheat, with 27.6 million ton/year imported by the MENA region from 2000 to 2012, followed by maize (14.4 million ton/year), barley (9.0 million ton/year), and rice (3.7 million ton/year).

2.3 Degree and eigenvector centralities for analyzing the structure of VWT

2.3.1 Nonscaled and scaled in-degree centralities of VWT

Understanding the VWT structure is important for quantifying the amount of import and export because the VWT structure can represent whether it would be sustainable or vulnerable. For example, if a country imports considerable amounts of virtual water through the food trade from just a few exporters, the structure of VWT in this country might be impressionable by exporters. However, if a country is connected with many exporters in VWT, it can have a resilient structure for global changes. A few studies have been conducted on the analysis of the structure of the VWT using a network-based approach (Konar et al., 2012; Dalin et al., 2012; Lee et al., 2016).

In this study, we analyzed the links of the VWT network for identifying the VWT structure using degree centrality, that is the number of degree incidents on a given node (Freeman 1979). In addition, the degree centrality is divided into in- and out-degree centralities, depending on the direction. In-degree is based on the number of lines (or volume) directed to the node. and out-degree is based on the number of lines (or volume) that the node directs to. In this study, we focused on the in-degree centrality because the MENA region includes representative importing countries. An importer accompanying an increased in-degree centrality has expanded connectivity with exporters, meaning that this importer could cope with an accidental disconnection from a certain exporter. In addition, the in-degree centrality, based on the number and volume of links in the

VWT network, is expressed according to the nonscaled in-degree centrality (NSInDC), that is based on the number of links, and the scaled in-degree centrality (SInDC), that is based on the volume of links.

$$NSInDC_i = \sum_j^N Link_{ij}/(N-1), \tag{6}$$

$$SInDC_i = \sum_j^N Flow_{ij}/(N-1), \tag{7}$$

where $NSInDC_i$ is the nonscaled in-degree centrality of country i, and $Link_{ij}$ is the number of links between the ith and jth countries. The symbol $SInDC_i$ is the scaled in-degree centrality of country i, and $Flow_{ij}$ is the volume of virtual water traded between the ith and jth countries. Moreover, N is the total number of countries.

Through NSInDC and SInDC, we analyzed the vulnerable expansion (or reduction) and robust expansion (or reduction) in the VWT network in the MENA region. For example, the vulnerable expansion in the network indicates that the amount of flow to a node increases but the number of connections to other nodes decrease. This is represented by high-levels of SInDC and low-levels of NSInDC. The importer country that is associated with vulnerable expansion has an increased quantity of products from only a few exporters.

2.3.2 Eigenvector centralities of VWT

The eigenvector centrality could be used for identifying influential countries who could affect the entire network. In other words, the entire VWT can be affected by a few influential countries, and it is important to identify these countries for understanding and estimating the change of the entire structure of the VWT. An eigenvector centrality can measure the influence of each country in the entire VWT, and it is related not only to its own connection pattern but also to the connections of other countries to it. Therefore, a country is more influential if it is considered in relation to the countries that are influential themselves (Ruhnau, 2000). The eigenvector centrality assigns relative centrality to all of the countries in the VWT, based on the principle that connections to high-level centrality countries contribute more to the centrality of the countries compared to equal connections to low-level centrality countries (Ruhnau, 2000; Lee et al., 2016). Therefore, the eigenvector centrality of the country is related to both the number of links to partners and their centralities (Ruhnau, 2000). Bonacich (1972) defined the centrality $c(v_i)$ of a node (country) v_i as the positive multiple of the sum of adjacent centralities, as follows,

$$\lambda c(v_i) = \sum_{j=1}^n \alpha_{ij} c(v_j) \qquad \forall i. \tag{8}$$

In matrix notation, and assuming that $c = (c(v_i), \ldots, c(v_n))$, the above equation yields

$$\mathrm{Ac} = \lambda \mathrm{c} \tag{9}$$

This type of equation is solved using eigenvalues and eigenvectors, where A is a square matrix, and λ is a scalar, known as the eigenvalue associated with the eigenvector c defined as a column vector. Eigenvector centrality is determined by calculating the principal eigenvector that has the largest eigenvalue among all eigenvectors. A non-negative eigenvector with the maximal eigenvalue exists. We refer to a non-negative eigenvector ($c \geq 0$) of the maximal eigenvalue as the principal eigenvector, and we call the entry $c(v_i)$ the eigenvector-centrality of node (country) v_i (Ruhnau, 2000).

3 Results and Discussion

3.1 Trade-offs between national water-land savings and food security through food trade in the MENA region

Food import could cause a decrease of food security, which can be a particularly critical issue in the MENA region. This is because the countries in the MENA region have very low food self-sufficiencies. For example, Egypt is one of the agricultural countries in the MENA region, and produced 20.5 million ton/year of barley, maize, wheat, and rice, which was 47 % of total production in the MENA region. However, 13.4 million ton of barley, maize, wheat, and rice was imported annually, and it was 40 % of domestic supply in Egypt. To sum up, in the MENA region, food security is a significant issue and some countries have tried to increase domestic production for food security.

However, we need to consider trade-offs between food security and national water-land management. In order to increase the food security, additional water and land should be required for increasing domestic production. Therefore, we estimated the national water and land savings by importing crops, that is a negative factor for food security. Table 3 shows that the green and blue water savings by barley, maize, and wheat imports in Saudi Arabia were 2.0 and 7.8 billion m³/year, respectively. This means that the contribution of import of barley, maize, and wheat on water security in Saudi Arabia was significant. In the case of Egypt, most of the water saving occurred based on the imports of wheat and maize. Approximately 7.5 billion m³/year of blue water was saved by importing wheat. Specifically, the internal water resources in Egypt are only 1.8 billion m³/year, therefore, if the exporting countries ban the export of wheat to Egypt, a significant water scarcity would occur.

The crop import could result in a large amount of land savings. In Saudi Arabia, land savings based on the import of barley, maize, and wheat, amounted to 1.6 million ha/year, and Lebanon was also strongly influenced by the impact of crop import on land savings. For example, approximately 0.24 million ha could be saved by crop imports, comprising 36% of the agricultural area in Lebanon, that indicates that the crop trade in Lebanon has significant benefits in terms of land resources compared to water resources.

These results can elicit useful information for analyzing the trade-off between food and water-land securities in the MENA region in terms of sustainable development. However, water saving indicates the virtual water saving, and sometimes it is larger than the total water resources in some countries. However, these results showed that the increase of food security is accompanied by numerous water requirements in the MENA region. Additionally, the saved land is not always suitable for agricultural areas. Some crops are required for the specific type of land, and the productivity is also different based on soil. Even if we can save land, there is the limitation for considering the land saving as an agricultural land saving in accordance to this study.

Table 3. The amount of water and land savings through importing crops in the MENA region from 2000 to 2012.

3.2 The VWT in the MENA region from 2000 to 2012

3.2.1 Virtual water import in the MENA region

The total amount of green and blue water imported by each Arab country from 2000 to 2012 respectively reached 921.2 and 80.5 billion m³ in the MENA region, as shown in Table 4 and Figure 1. The largest volume of green water was imported annually by Egypt (19.1 billion m³/year), followed by Saudi Arabia (11.9 billion m³/year). In addition, the largest amount of blue water was imported annually by Saudi Arabia (1.2 billion m³/year), followed by the UAE (0.9 billion m³/year). Over 70% of the green water imported annually into the MENA region based on the trade of barley (approximately 8.5 billion m³/year) was occupied by Saudi Arabia. The amount of virtual water imported based on the trade of maize was 13.0 billion m³/year, with Egypt being the primary importer of 31% of the total imported amount into the MENA region.

Generally, rice is cultivated in paddy fields, and the blue water footprint of rice in these fields is larger than other cereal crops in various countries. For example, the global average of the blue water footprint of rice is 584 m³/ton but that for wheat is 343 m³/ton (Chapagain and Hoekstra 2011; Mekonnen and Hoekstra 2010). Therefore, the importers of rice also import a lot of water. Approximately 3.0 billion m³/year of blue water were imported in the rice trade from 2000 to 2012, and Saudi Arabia, UAE, and Iraq, were the primary importers. The largest volume of virtual water imported by the MENA region was owing to the trade of wheat. The annual amount of virtual water imported based on the trade of wheat in the MENA region from 2000 to 2012 was approximately 42.6 billion m³/year, but the amount of blue water was only 2.0 billion m³/year. Over 35% of the virtual water imported through the wheat trade was imported by Egypt (15.7 billion m³/year).

We also estimated the amount of virtual water imported per capita (VWIcap), as shown in Figure 2, which shows the differing viewpoints regarding food and water securities. If we consider only the total amount of imported virtual water, the UAE may not be considered to be a significant importer because the population and area of UAE is much smaller than those of the MENA other countries, such as Saudi Arabia. However, the virtual water import per capita in the UAE is larger than that of Saudi

Arabia, thus indicating that the dependency on virtual water imported from exporters in the UAE is much more significant than in Saudi Arabia. For example, the VWIcap was 1266.6 m³/cap/year in the UAE, which was the largest value in the MENA region. The UAE is strongly dependent on the import of virtual water, even though the UAE imports only 4.2 billion m³/year of virtual water. The VWIcap increased significantly in Saudi Arabia and Libya from 2000 to 2012. Saudi Arabia and Libya imported approximately 453.4 and 497.8 m³/cap/year, respectively, of virtual water more in 2012 than in 2000. Saudi Arabia was the second largest importer in the MENA region, and its VWIcap was also the fifth highest in the MENA region.

Table 4. The amount of green and blue water imported in the MENA region from 2000 to 2012.

Figure 1. The total amount of virtual water imported by each country in the MENA region from 2000 to 2012, separated into green (upper) and blue (lower) water. The pie graph shows the annual import and proportion of each crop, and the size of the pie indicates the amount of annual virtual water imported from 2000 to 2012**.**

Figure 2. Virtual water imported per capita in the MENA region from 2000 to 2012.

3.2.2 Virtual water export to the MENA region

We also focused on the volume of virtual water exported to the MENA region by each exporter from 2000 to 2012, as shown in Figure 3. Based on the trade of barley, Ukraine exported 41.1 billion m³ of green water to the MENA region that amounted to 27% of the total green water imported in the MENA region based on barley. In terms of blue water traded through barley, five exporters (Germany, Australia, the Russian Federation, Ukraine, and India) provided 78% of the total blue water imported in the MENA region based on barley. Based on the trade of maize, Argentina contributed 40% of the total amount of green water imported by the MENA region based on maize, but the blue water imported by the MENA region was primarily from the USA. Based on the trade of rice, the major virtual water exporters to the MENA region were India, Thailand, and Pakistan. In particular, 30.4 billion m³ of blue water were imported from these countries from 2000 to 2012, which comprised 78% of the blue water imported by the MENA region based on rice. Wheat was the most representative crop imported by the MENA region. The Russian Federation and the USA provided 25% (140.6 billion m³) and 21% (111.2 billion m³) of the total amount of green water imported in the MENA region based on the trade of wheat in 2000 to 2012, respectively, and the remaining 55% was divided among several exporters, including Australia, Canada, France, and Ukraine.

Figure 3. Quantities of green water export (GWE) and blue water export (BWE) from the primary exporters to the MENA region from 2000 to 2012

3.3 The change of VWT structure in the MENA region

We analyzed the degree centralities of NSInDC and SInDC from 2000 to 2012 in the MENA region, and identified the countries who had the vulnerable expansion or reduction in the VWT network.

Figure 4 shows the NSInDC and SInDC patterns in the VWT network in accordance to each country in the MENA region. If the specific country has both large NSInDC and small SInDC, this country constructs the connection with various exporters but imports a small amount of virtual water. Specifically, Egypt and Yemen showed that NSCInD was lower but SInDC was higher than other countries, thus indicating the intensive connectivity with a few exporters. In contrast, Saudi Arabia had larger SInDC than other countries expect for Egypt, while the NSCInD was also highest in the MENA region. Accordingly, Saudi Arabia had a more distributed structure regarding VWT. UAE and Iraq had similar SInDC in 2012 but NSInDC was quite different (UAE (0.46) and Iraq (0.27)). Furthermore, SInDC in Morocco (96.45) was larger than UAE (83.41) but NSInDC in Morocco (0.26) was smaller than UAE (0.46). In comparison to UAE, Morocco had intensive connections with fewer exporters compared to UAE.

Based on the temporal changes of NSInDC and the SInDC during two periods (2000–2006 and 2006–2012), the MENA region countries were divided into four types (I–IV), as shown in Figure 5. The listed numbers in Figure 5 represent each Arab country. For example, the number 1 is assigned to Algeria. The x-axis indicates the NSInDC and the y-axis indicates the SInDC. Therefore, if the specific country in the MENA region is located at a higher level in the x-axis and at a lower level in the y-axis, this country has established connections with more exporters but has a decreased virtual water imports. Type I countries show a robust expansion in the virtual water import. Additionally, the countries in this type increased the connectivity and volume of virtual water imported, simultaneously. Type II countries increased the volume of virtual water imported without expansion of connectivity. Type III and type IV countries showed reductions in the virtual water import with and without reduction of connectivity, respectively.

In the early 2000s, most of countries in the MENA region tried to expand their trade structure by increasing both the connectivity to the exporters and the volume of the imported virtual water. In Bahrain, Omen, Qatar, Yemen, Saudi Arabia, Lebanon, and UAE, the NSInDC of the VWT network increased significantly from 2000 to 2006, which means that the trade connectivity expanded. The expanded structure of the VWT indicates that the Arab countries were connected to various exporters, and that this structure can be a resilient structure for global changes. In particular, the import of food crops is an essential factor in food security in the MENA region, even if food self-sufficiency is increased by increasing domestic production. However, Egypt had the largest SInDC but NSInDC was ranked 6th among the MENA region countries. In 2006, Egypt and Saudi Arabia both expanded the connectivity in the VWT network, as shown by the increasing NSInDC.

However, the VWT has become a more vulnerable structure in the MENA region in recent years. Most of the Arab countries increased the volume of the imported virtual water, but the number of exporters that linked to the Arab countries decreased or increased insignificantly from 2006 to 2012. In particular, in 2012, most of countries kept their connectivities or reduced them, except for Algeria, Iraq, Libya, and UAE. For example, Figure 6 shows that the virtual water imported in Lebanon significantly increased from 2006 to 2012, but NSInDC decreased in 2012. In 2000 Lebanon imported most of the virtual water from the USA, Argentina, and Australia. Thus, VWT in Lebanon was strongly dependent on these exporters. However, Lebanon expended the VWT in 2006 and Russian Federation, Turkey, and Kazakhstan, contributed to virtual water imports in Lebanon. Accordingly, the structure of VWT in Lebanon approached a distributed network. However, the VWT in 2012 showed that it was dominated by Ukraine and Russian Federation, even if Lebanon imported more virtual water in 2012 than 2006. Therefore, Lebanon should consider not only the amount of virtual water but also the structure of VWT for sustainable food security subject to the condition of a strong dependency on crop import. These results indicate that the dependence of the MENA region on virtual water import increased rapidly recently with the large increase in the imported volume of virtual water. However, the connectivity of the VWT in the MENA region has not increased as much as the volume of virtual water imported increased.

We analyzed the influence of each country on the entire VWT network of the MENA region using eigenvector centrality, as shown on Figure 7. In 2000, Egypt and Saudi Arabia were identified as the most influential importers in the MENA region, and the USA and Australia were the most influential exporters. Accordingly, the entire VWT in the MENA region could be affected by these importers and exporters. This means that the change of the trade policy or food management in these countries could change the structure of VWT in the MENA region. In 2006 and 2012, the influential countries in the MENA region were still Egypt and Saudi Arabia, but the influential exporters moved to the Russian Federation, Ukraine, and Brazil.

Figure 4. Nonscaled and scaled in-degree centralities of each country in the MENA region in 2000, 2006, and 2012

Figure 5. Country types in the MENA region according to the changes of nonscaled and scaled in-degree centralities

Figure 6. Virtual water import from exporters to Lebanon in 2000, 2006, and 2012.

Figure 7. Eigenvector centrality of virtual water trade network in the MENA region at 2000, 2006, and 2012

3.4 Importance and limitations of water footprint and VWT in the MENA region from a policy perspective

Generally, the VWT is more related to resource management in exporting countries rather than importing countries because the embedded water in food trade indicates water resources that are consumed for producing food products in the exporting country. However, VWT is also considered as an important issue in importing countries in terms of water and food security. For example, the reduction of VWT might be related to water consumption by replacing imported food products by domestic food products.

However, the application of the concept of VWT is under critical discussion (Wichelns, 2010). First, water footprints formulate new concepts of water management, but it is difficult to link these to operating water resource systems. Water footprints are more related to the water consumption rather than water supply. We can quantify the water requirements for producing food products or water savings by importing them using the water footprint and VWT. However, the operations of the water facilities, for example reservoirs, desalination plants, and ground water pumping stations, are affected by monthly rainfall and ground water level, development of technologies, fertilizer usage, irrigation scheduling, and systems. Therefore, we need to realize that water footprint can be changed in accordance to various factors. Second, VWT could contribute to the connection of water management to food security. However, food trade is affected by the scarcity or affluence of other important resources, such as capital, labor, and land (Biewald et al., 2014). In particular, economic values, such as the price of food products, is the main driver in global food trade, but there is no global value established for virtual water. Therefore, it is difficult to apply virtual water to trade policy in terms of the economic efficiency. Therefore, policy makers or resource managers in the MENA region should not only consider the effects of VWT but also the difficulty in adapting virtual water to policies for resource management.

Despite these limitations, we believe that virtual water has a role in the achievement of sustainable water, land, and food security, even if there are limitations and difficulties in applying the virtual water concept. As mentioned above, the VWT can be a major resource in the MENA region. Accordingly, vulnerable VWT, for example, low connectivity, can be a risk element for future food security risk management. In particular, the MENA region is strongly dependent on food products from exporting countries that implies a strong dependency on water resource from exporting countries. Therefore, water shortages or low-food production in exporting countries might cause increasing food prices in the MENA region, but also increasing domestic water use for increasing domestic food production. The primary resources of water, energy and food are naturally interlinked. The degree of their interlinkages in the MENA is exceptionally high, thus creating a higher degree of risks and vulnerability. Therefore, understanding these interlinkages and quantifying them in an attempt to better understand this complex system of systems is crucial. This requires the synergistic effort of multiple disciplines, including contributions from various technologies, science, policies, health, communication, and economics, at local processes and system level scales. In this study, we believe that the VWT in the MENA region can be the key factor for bridging water and food, and it is important to quantify the influence of trade on water and food management. In addition, this study revealed vulnerability (or robust) expansion (or reduction) and influential traders in the VWT network in the MENA region, based on in-degree and eigenvector centrality indices. If a country in the MENA region has low connectivity but an increased import of virtual water, this country should re-evaluate their vulnerable trade structure and change the trade policy or water-food management.

4. Conclusions

The import of water in virtual form based on VWT could develop into a major water portfolio that dominates water management in the water-scarce countries of the MENA region. Since the introduction of the virtual water concept, various studies have been conducted to quantify the volume of the VWT. In water-deficit areas, such as the MENA region, the VWT can offer new perspectives for understanding and solving water stress and scarcity. The amount of imported virtual water is regarded as the most important factor in determining water and food security, and the water and land savings based on crop imports in the MENA region could explain and underline the importance of international trade.

In particular, the interlinkages of key natural resource sectors and the improved production efficiency are considered a win–win strategy for environmental sustainability for current or future generations (Ringler et al., 2013). Nexus frameworks identify key issues in food, water, and energy securities through the lens of sustainability, seeking to predict and protect against future risks and resource insecurities (Biggs et al., 2015). The core of the Nexus concept is that the production, consumption, and distribution of water, energy, and food, are inextricably interlinked. Thus, decisions made in one sector typically impact the other sectors (Mohtar and Daher, 2014). Therefore, we believe that virtual water can be a useful interlinking parameter among water, food, and land, within the Nexus system. In addition, VWT and water-land savings by trade in this study can be used for supporting decisions through the Nexus system.

In summary, policy makers can benefit by considering both the quantitative impacts of VWT and the structural changes of VWT, such as vulnerable expansion (or reduction) in the MENA region. The intensity and connectivity of VWT, which were analyzed in this study, can be the major components needed for integrating food and water policies in the MENA region. Correspondingly, this study might provide important information to policy makers for evaluating future scenarios about resource management toward sustainability in the MENA region.

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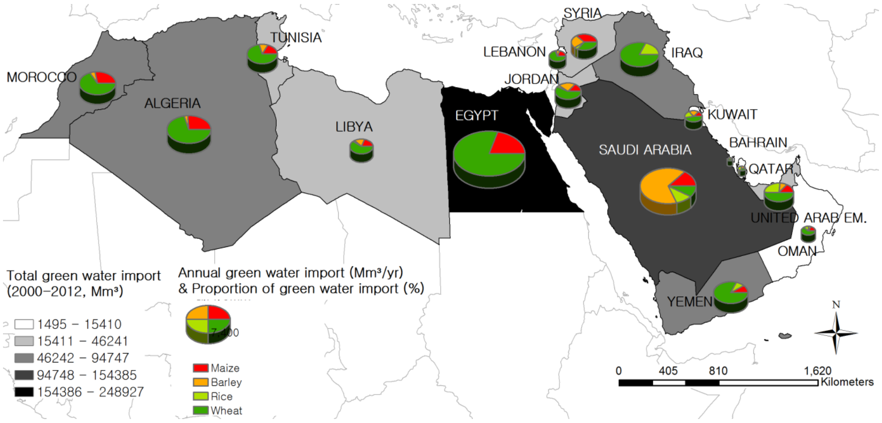
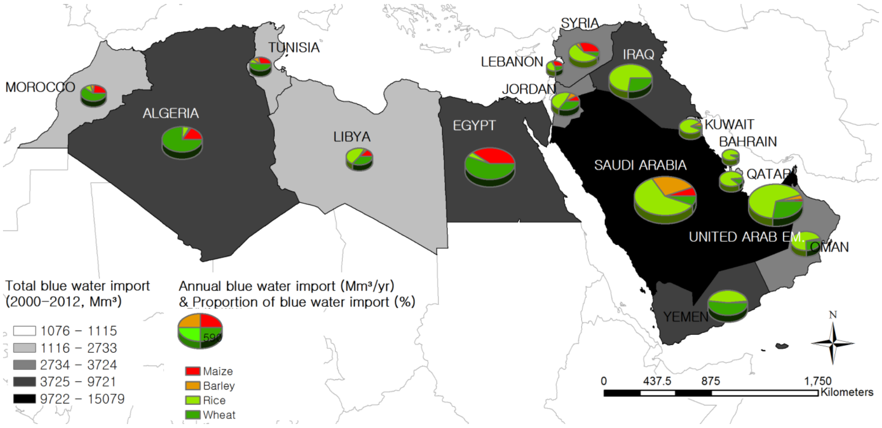


(a) Green water imports



(b) Blue water imports

Figure 1. Total amount of virtual water imported by each country in the MENA region from 2000 to 2012 classified into green (upper) and blue (lower) water. The pie graphs show the annual imports and proportions of each crop, while the size of the pie indicates the amount of annual virtual water imported from 2000 to 2012

Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2018-398
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 17 September 2018

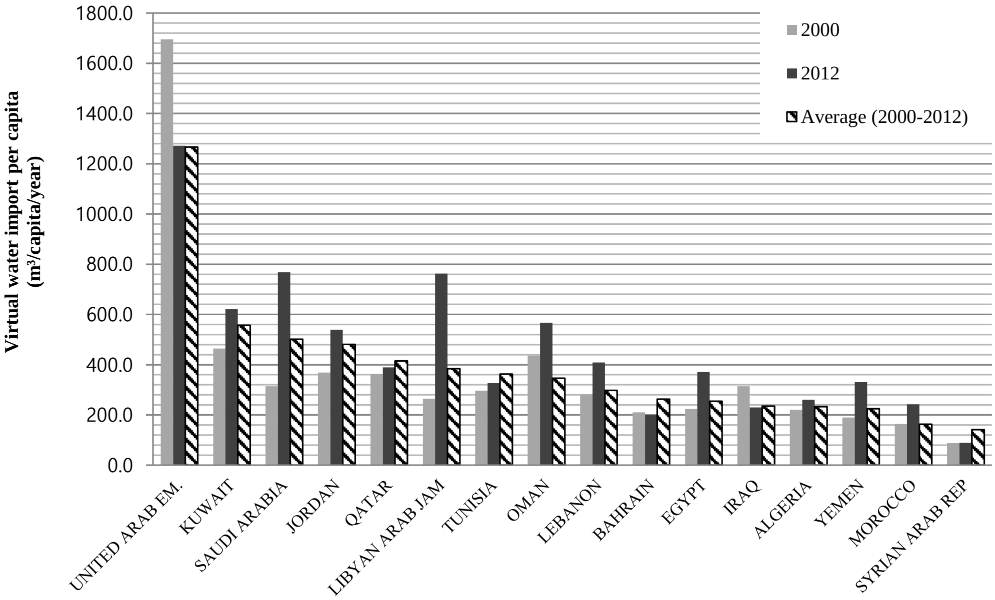
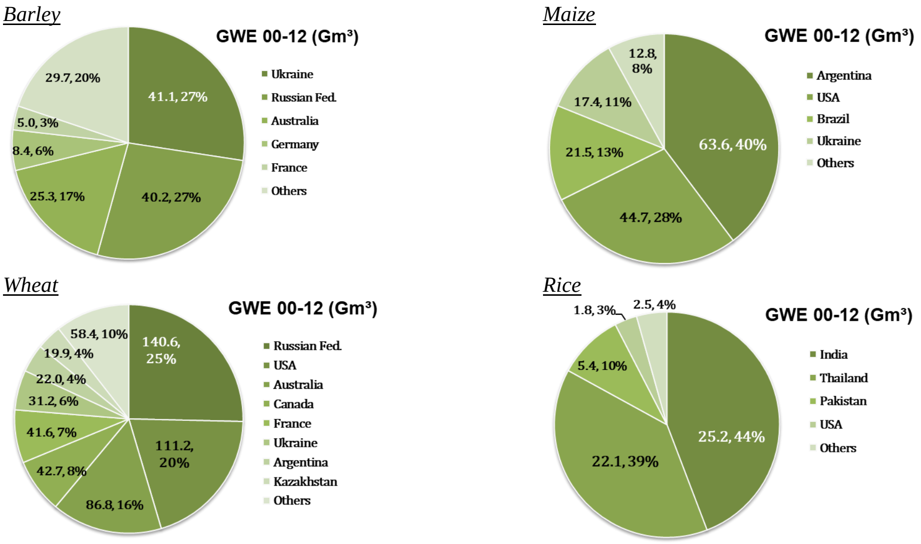
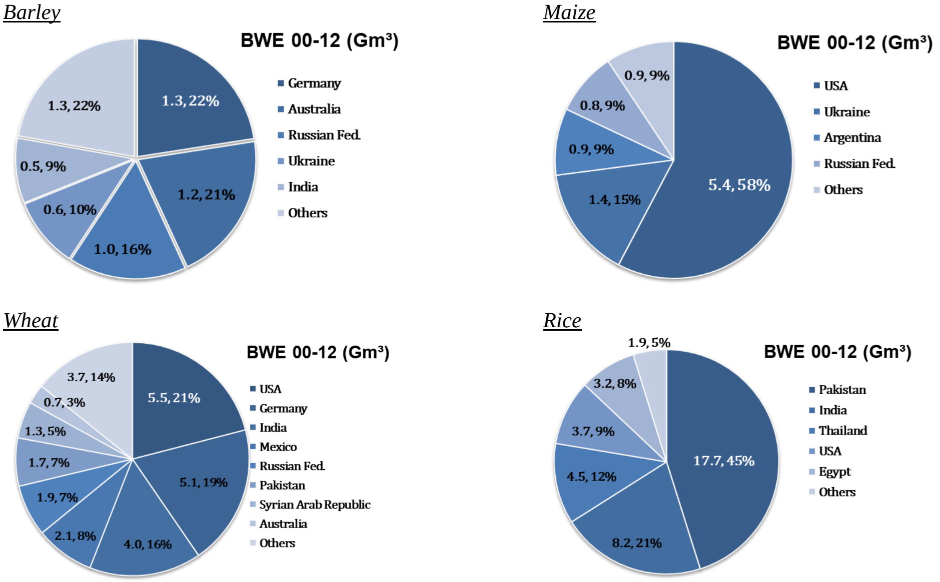


Figure 2. Virtual water imported per capita in the MENA region from 2000 to 2012

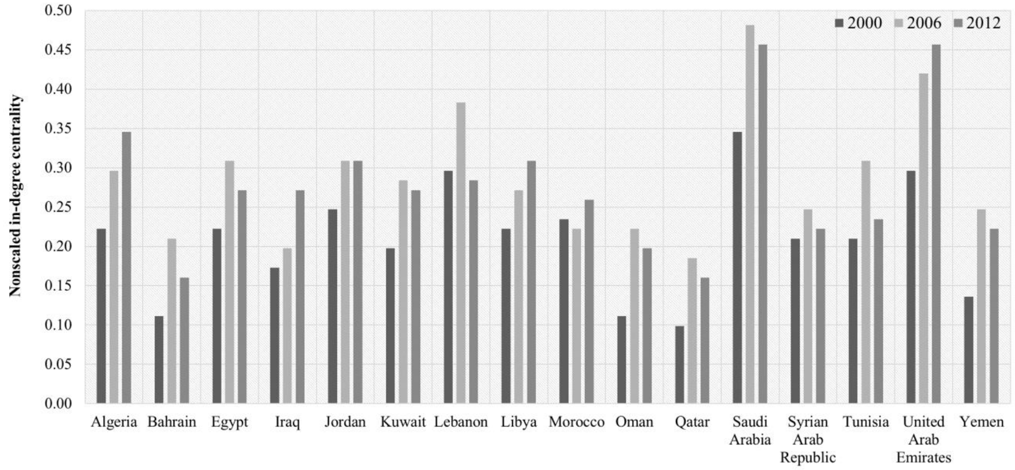


(a) Total green water export (GWE) during 2000-2012

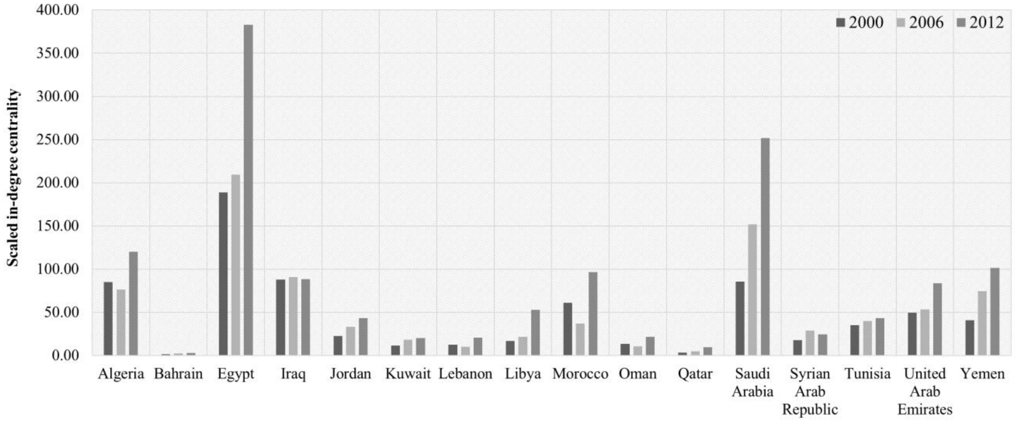


(b) Total blue water export (BWE) during 2000-2012

Figure 3. Quantities of green water exports (GWE) and blue water exports (BWE) from the primary exporters to the MENA region from 2000 to 2012

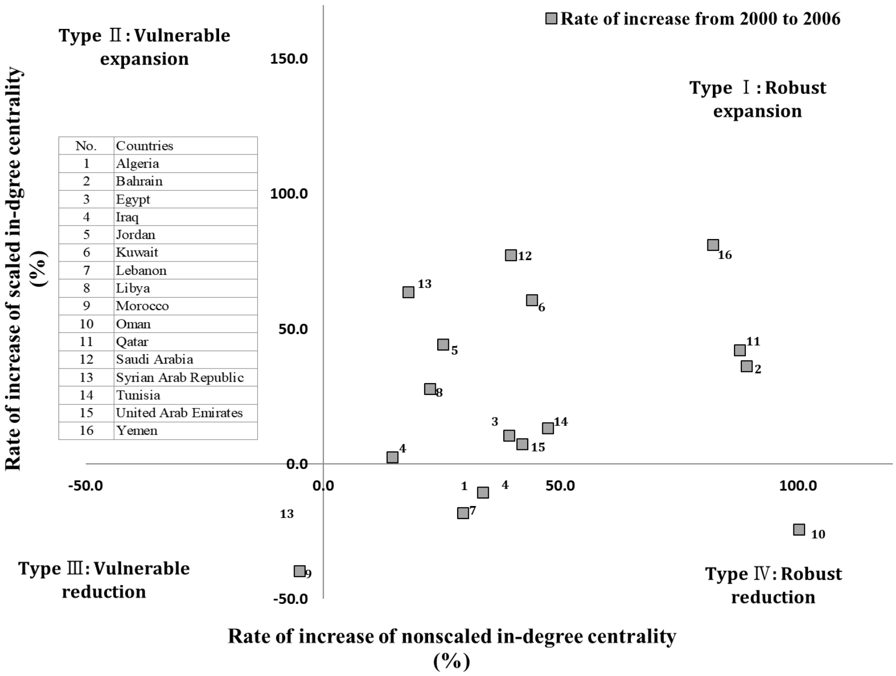


(a) Nonscaled in-degree centrality



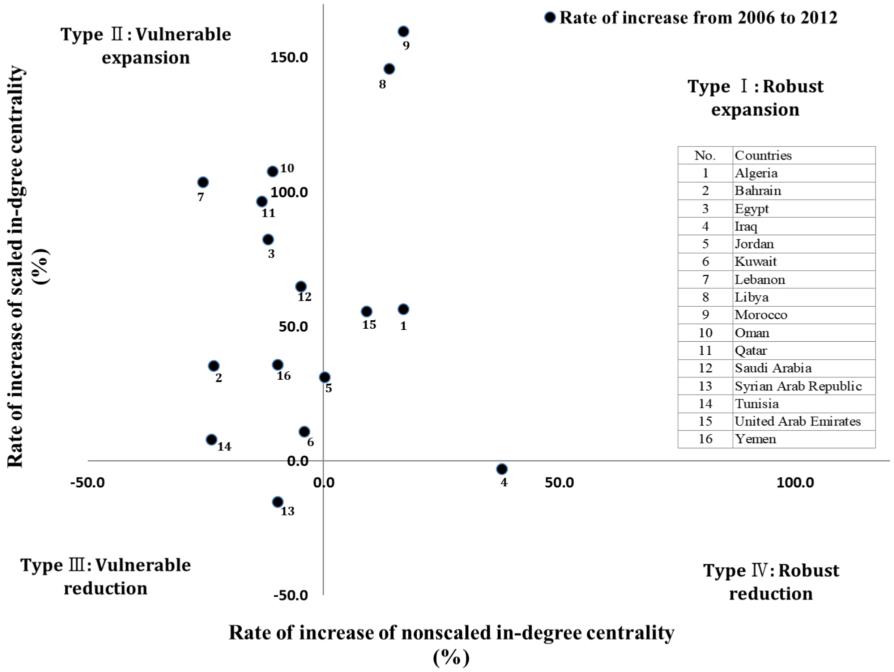
(b) Scaled in-degree centrality

Figure 4. Nonscaled and scaled in-degree centralities of each country in the MENA region in 2000, 2006, and 2012



No.	Countries
1	Algeria
2	Bahrain
3	Egypt
4	Iraq
5	Jordan
6	Kuwait
7	Lebanon
8	Libya
9	Morocco
10	Oman
11	Qatar
12	Saudi Arabia
13	Syrian Arab Republic
14	Tunisia
15	United Arab Emirates
16	Yemen

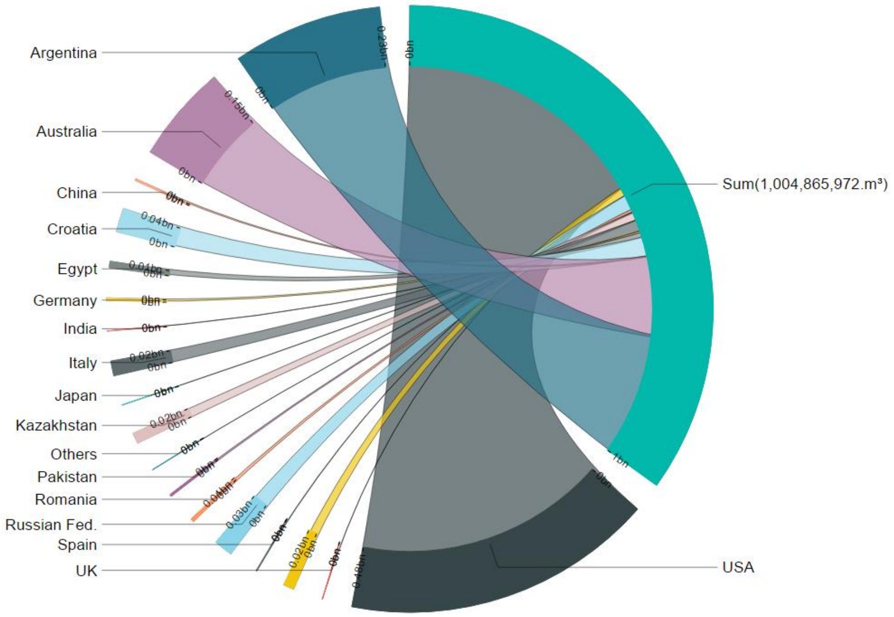
(a) Changes of in-degree centrality from 2000 to 2006



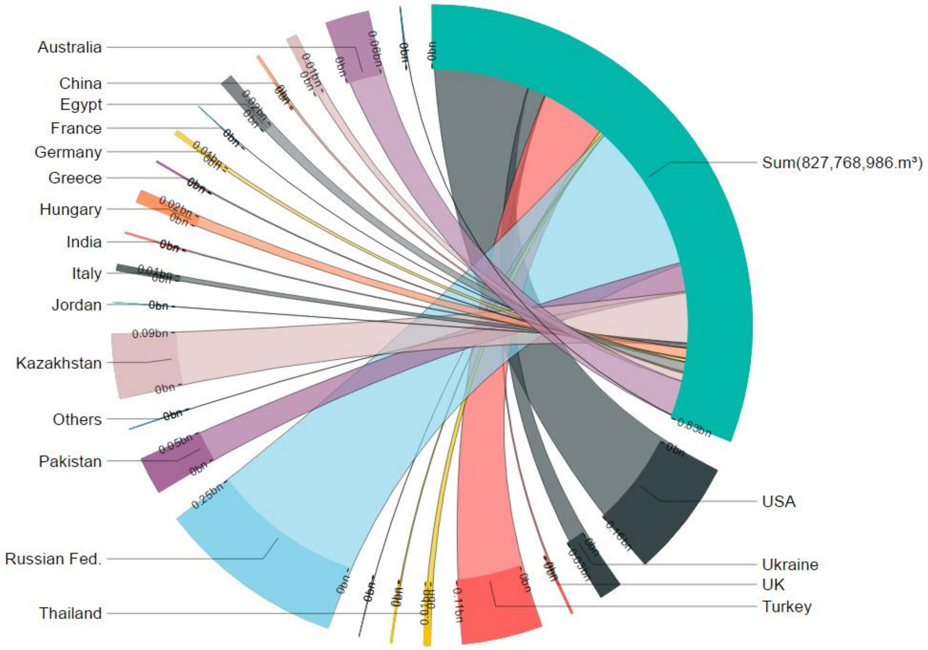
No.	Countries
1	Algeria
2	Bahrain
3	Egypt
4	Iraq
5	Jordan
6	Kuwait
7	Lebanon
8	Libya
9	Morocco
10	Oman
11	Qatar
12	Saudi Arabia
13	Syrian Arab Republic
14	Tunisia
15	United Arab Emirates
16	Yemen

(b) Changes of in-degree centrality from 2006 to 2012

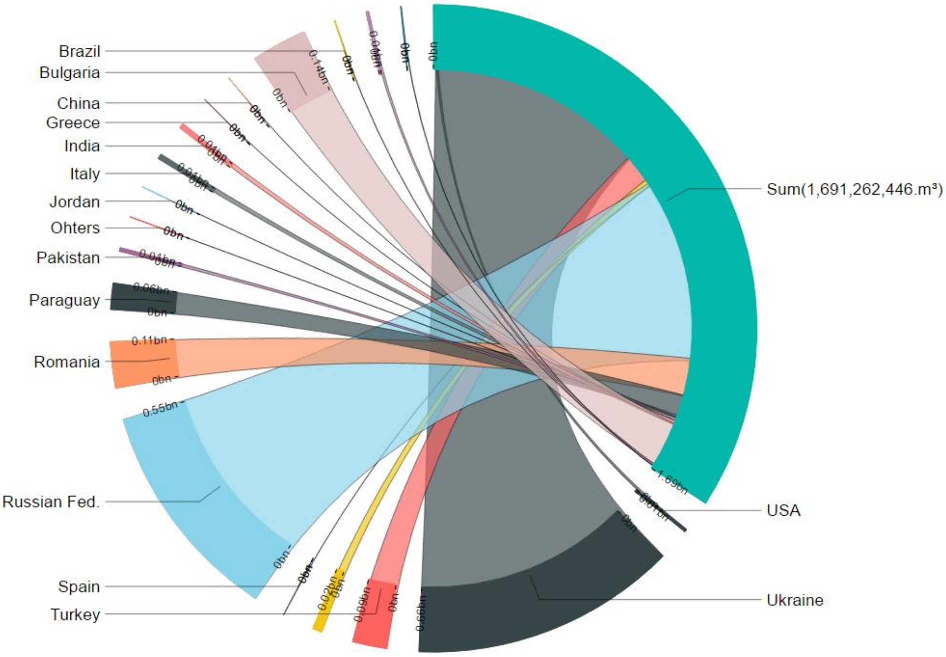
Figure 5. Country types in the MENA region according to the changes of nonscaled and scaled in-degree centralities


Argentina
Australia
China
Croatia
Egypt
Germany
India
Italy
Japan
Kazakhstan
Others
Pakistan
Romania
Russian Fed.
Spain
UK
USA
Sum(1,004,865,972.m³)
0.23bn
0bn
0.15bn
0.04bn
0.02bn
0.03bn
1bn
0.48bn

(a) 2000


Australia
China
Egypt
France
Germany
Greece
Hungary
India
Italy
Jordan
Kazakhstan
Others
Pakistan
Russian Fed.
Thailand
USA
Ukraine
UK
Turkey
Sum(827,768,986.m³)
0.06bn
0.01bn
0bn
0.02bn
0.04bn
0.09bn
0.05bn
0.25bn
0.11bn
0.83bn
0.16bn
0.03bn

(b) 2006



(c) 2012

Figure 6. Virtual water imports from exporters to Lebanon in 2000, 2006, and 2012.
(bn indicates billion m³)

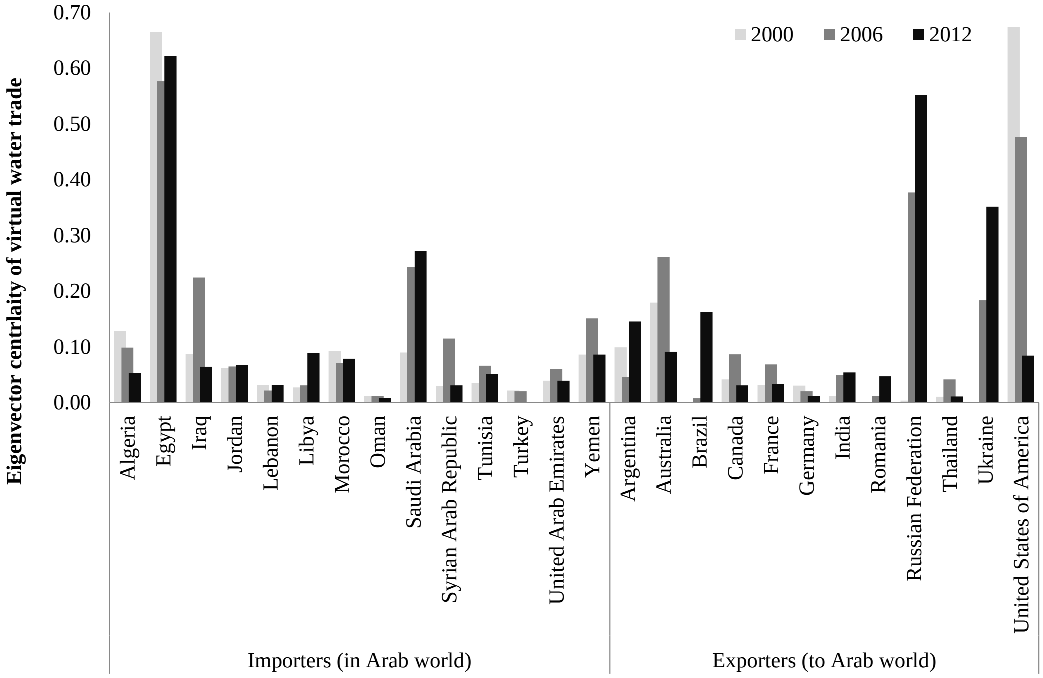


Figure 7. Eigenvector centralities of the virtual water trade network in the MENA region in 2000, 2006, and 2012

Table 1. Water and land footprints of four major crops in the MENA region

Countries in the MENA region	**Water footprint (m^3/ton)**								**Land footprint (ha/ton)**			
	Barley		Maize		Wheat		Rice					
	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint	Green water footprint	Blue water footprint	Barley	Maize	Wheat	Rice
ALGERIA	2859.0	-	964.1	-	3290.0	65.2	1080.8	-	0.72	0.27	0.72	-
EGYPT	619.2	1694.7	140.8	1078.2	214.8	903.5	59.0	1003.1	0.51	0.13	0.16	0.10
IRAQ	3459.7	4321.4	587.3	1812.2	3069.2	2818.3	256.2	6574.7	1.22	0.42	0.72	0.37
JORDAN	3167.8	320.3	126.6	-	2267.0	988.7	-	-	1.37	0.05	0.86	-
KUWAIT	929.3	2256.3	41.2	207.9	955.4	2287.7	-	-	0.48	0.05	0.50	-
LEBANON	1919.9	-	507.6	14.4	1556.0	97.0	-	-	0.54	0.27	0.36	-
LIBYA	6417.6	1808.2	1151.1	-	4360.2	1542.9	-	-	2.04	0.45	1.29	-
MOROCCO	3692.3	-	3541.0	3182.9	2758.0	244.6	293.0	1278.0	1.13	1.43	0.69	0.16
OMAN	322.9	2336.2	-	-	842.4	1938.5	-	-	0.33	-	0.30	-
QATAR	485.6	1714.3	78.5	502.9	678.6	1626.3	-	-	0.33	0.07	0.44	-
SAUDI ARABIA	193.6	799.8	366.6	1270.1	238.4	1093.2	-	-	0.18	0.19	0.19	-
SYRIA	5084.0	41.6	347.3	1573.4	1454.2	440.1	273.2	-	1.61	0.25	0.42	-
TUNISIA	3561.1	75.1	-	-	2375.0	71.8	-	-	0.94	-	0.55	-
UAE	-	-	-	-	1563.5	507.7	-	-	0.13	0.05	0.24	-
YEMEN	1904.6	3234.4	1726.2	2950.8	1804.4	2355.5	-	-	1.22	0.71	0.64	-

Table 2. Cultivation area, production, and the quantity of crops imported in the MENA region from 2000 to 2012

Countries in the MENA region	Annual cultivation area (ha/year)				Annual production (ton/year)				Annual import (ton/year)			
	Barley	Maize	Wheat	Rice	Barley	Maize	Wheat	Rice	Barley	Maize	Wheat	Rice
ALGERIA	760,545	308	1,658,197	-	1,049,710	1,128	2,313,464	-	233,887	2,112,527	5,363,580	47,080
EGYPT	68,103	876,153	1,180,644	625,626	134,034	6,812,845	7,549,253	6,023,684	24,805	5,073,779	8,295,988	46,292
IRAQ	914,074	128,842	1,451,219	85,182	751,099	307,682	2,009,972	232,040	35,378	18,960	2,545,919	742,394
JORDAN	31,158	947	20,116	-	22,757	17,514	23,379	-	487,593	385,936	792,508	137,442
KUWAIT	1,058	290	173	-	2,191	5,855	345	-	178,432	134,373	284,684	171,451
LEBANON	13,515	949	45,380	-	24,834	3,579	126,623	-	49,278	289,707	367,370	46,087
LIBYA	191,641	1,356	165,469	-	94,107	2,997	128,149	-	226,317	429,407	803,545	122,579
MOROCCO	2,118,032	226903	2,910,977	5,876	1,867,670	159,127	4,200,596	36,936	392,639	1,446,836	2,994,446	13,307
OMAN	1,002	-	426	-	3,027	-	1,432	-	35,829	99,525	288,134	118,802
QATAR	947	94	15	-	2,841	1,329	34	-	33,286	3,914	47,798	87,312
SAUDI ARABIA	12,279	16,689	374,414	-	68,366	86,181	1,997,598	-	6,252,893	1,600,081	700,703	1,009,384
SYRIA	1,313,101	53,405	1,667,229	-	817,609	211,675	4,008,420	-	393,029	1,319,461	454,904	201,690
TUNISIA	385,189	-	722,038	-	411,431	-	1,302,438	-	407,455	737,754	1,525,848	17,453
UAE	14	144	18	-	111	2,931	74	-	215,321	399,987	1,063,996	683,336
YEMEN	39,276	40,774	110,138	-	32,248	57,329	173,437	-	2,845	343,919	2,096,970	279,136

Source: FAOSTAT (http://www.fao.org/faostat/)

Table 3. The amounts of water and land savings based on imported crops in the MENA region from 2000 to 2012

Countries in the MENA region	**Water savings (million m³/year)**						**Land savings (thousand ha/year)**		
	Barley		Maize		Wheat				
	Green water	Blue water	Green water	Blue water	Green water	Blue water	Barley	Maize	Wheat
ALGERIA	669.0	-	2,037.2	-	17,647.6	349.9	169.5	577.0	3,844.7
EGYPT	15.5	42.4	714.3	5,470.5	1,781.9	7,495.6	12.7	652.5	1,297.4
IRAQ	121.1	151.3	11.2	34.4	7,814.1	7,175.5	42.6	8.0	1,838.2
JORDAN	1,545.9	156.3	48.9	-	1,797.7	784.0	668.2	20.9	682.3
KUWAIT	165.4	401.6	5.5	27.9	272.3	652.0	86.0	6.6	142.9
LEBANON	94.1	0.0	147.2	4.2	571.0	35.6	26.7	76.9	131.5
LIBYA	1,450.4	408.6	493.8	-	3,505.6	1,240.5	460.2	194.1	1,038.1
MOROCCO	1,451.1	-	5,123.8	4,605.6	8,257.3	732.3	445.7	2,063.3	2,074.8
OMAN	11.6	84.1	0.0	-	242.6	558.3	11.9	-	85.7
QATAR	16.0	56.6	0.3	2.0	32.6	78.1	11.0	0.3	21.2
SAUDI ARABIA	1,210.5	5,001.5	586.5	2,032.1	167.1	766.3	1,123.1	309.8	131.4
SYRIA	1,998.0	16.3	458.1	2,075.3	661.6	200.3	631.2	332.8	189.2
TUNISIA	1,449.4	30.5	-	-	3,624.2	109.6	381.0	-	846.0
UAE	-	-	-	-	1,663.6	540.2	27.1	19.7	258.8
YEMEN	5.7	9.7	593.8	1,015.1	3,783.8	4,939.4	3.7	244.7	1,331.7

* Water and land savings by rice import was not calculated because of the lack of the data of water and land footprints in the MENA region

Table 4. The amounts of green and blue water imported in the MENA region from 2000 to 2012

Countries in the MENA region	**Import of green water (million m^3/year)**					**Import of blue water (million m^3/year)**				
	Barley	Maize	Wheat	Rice	Total	Barley	Maize	Wheat	Rice	Total
ALGERIA	242.0	1,883.6	5,104.8	57.8	7,288.2	7.8	76.6	371.1	33.5	489.0
BAHRAIN	0.4	7.5	62.7	44.4	115.0	0.2	0.3	7.1	78.2	85.8
EGYPT	37.3	3,798.4	15,254.1	58.4	19,148.2	1.1	295.6	418.6	32.5	747.8
IRAQ	33.2	16.7	4,645.8	1,027.8	5,723.5	2.2	1.3	153.9	404.8	562.2
JORDAN	656.8	364.2	1,483.9	81.2	2,586.1	20.8	20.8	84.5	115.0	241.1
KUWAIT	257.0	159.1	557.7	211.6	1,185.4	9.7	2.3	10.2	138.1	160.3
LEBANON	84.7	211.0	749.5	30.0	1,075.2	2.3	25.6	18.9	36.0	82.8
LIBYA	359.6	408.9	1,245.4	56.0	2,069.9	8.4	26.8	75.3	99.7	210.2
MOROCCO	318.6	1,383.2	3,345.0	8.9	5,055.7	12.1	46.1	118.8	20.4	197.4
OMAN	52.7	123.2	470.8	107.6	754.3	5.4	4.1	67.8	201.3	278.6
QATAR	50.9	6.4	76.4	77.6	211.3	2.4	0.3	19.1	146.9	168.7
SAUDI ARABIA	8,154.5	1,521.4	974.0	1,225.9	11,875.8	324.3	68.9	70.8	696.0	1,160.0
SYRIA	556.4	947.3	900.0	120.8	2,524.5	12.8	90.2	17.8	165.6	286.4
TUNISIA	409.8	611.7	2,507.7	27.8	3,557.0	16.0	40.7	73.9	11.6	142.2
UAE	315.7	465.8	1,671.8	859.5	3,312.8	28.5	14.3	249.3	612.5	904.6
YEMEN	3.1	406.1	3,597.3	392.7	4,399.2	1.6	8.2	247.3	220.8	477.9