Analysis of Trade-offs between Food Security and Water-Land Savings through Food Trade and Virtual Water 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 while decreasing domestic food production can contribute to water savings and hence to greater water security. However, increased domestic food production is better way to achieve food security, even if irrigation demands increase under projected climate changes. There is trade-off between food security and the savings of water and land through food trade, and this trade-off is a significant factor, especially in the MENA. This study analyses the impact of food trade on food security and water-land savings in the MENA region and in terms of virtual water trade (VWT). We estimate the total volume of virtual water imported for four major crops - barley, maize, rice, and wheat – between 2000 and 2012 to assess the impact on water and land savings, and food security. The largest volume of virtual water was imported by Egypt (19.9 billion m³/year), followed by Saudi Arabia (13.0 billion m³/ year). We concluded that Egypt could save 13.1 billion m³ in irrigation water and 2.0 million ha of land area by importing food rather than producing crops. In addition, the study revealed that the MENA region focused more on increasing the volume of virtual water imported during the period 2006-2012 with little attention to the expansion of connections with country exporters through VWT network analysis. The study sheds light on opportunities and risks associated with VWT and its role in food security and land management in the MENA region.

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

1 Introduction

The virtual water trade (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 in realistically assessing water scarcity for each country, projecting future water demand for food supply, increasing public awareness about water, and identifying water-wasting processes in production (Oki and Kanae, 2004). For water-scarce countries, achieving water security through 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, meaning that 13% of the water used for crop production in the world was not used for domestic consumption but rather for export in virtual form (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 climate 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 more water was required to produce animal foods than other foods (Falkenmark and Lannerstad, 2010).

The VWT could contribute to relieve water stress through using global water more efficiently, in the event of an increase in global food trade (Molden, 2007), and 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 those foods in exporting areas. Yang et al. (2006) revealed that the VWT could generate a global water saving because virtual water has flown primarily from countries of high crop water productivity to countries of low crop water productivity. In their study, globally, 336.8 km³/year of water were saved by the international trade of major food crops from 1997 to 2001, and 20.4% of the total global net virtual water import was imported to countries that have water availability below 1700 m³ per capita, such as Arab countries. Fader et al. (2011) calculated virtual water trade through trade of crop products, and compared with water requirement for producing crop products in each country for domestic consumption without international trade. Generally, exporters use less water for producing crop products than importers, thus the trade of crop products saves 263 km³/year of water, globally, representing 3.5% of the annual precipitation on cropland (Fader et al., 2011). In particular, water-scarce countries, such as China and Mexico, but also The Netherlands and Japan, saved large amounts of water by importing goods—from 25 to 73 km³/year of water—because they would need relatively large amounts of water to produce the goods they import. According to the study by Biewald et al. (2014), blue water, which means irrigation water supplied from artificial facilities such as reservoir, ground water pumping station or desalination station, was saved in importing countries through importing products by international trade, and it can bring 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 Arab countries by about 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 throughout the many 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 declining aquifer levels and the extraction of non-renewable 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 due to climate change. The zone of severely-reduced rainfall extends throughout the Mediterranean region and the northern Sahara (Hennessy et al., 2007). Milly et al. (2005) identify that climate change causes a drop in water run-off by 20% to 30% in most of Middle East North Africa (MENA) by 2050, mainly due to rising temperatures and lower precipitation. In addition, the regions including Syria, Lebanon, Israel, and Jordan will get drier, with significant rainfall decrease in the wet season.

However, the high dependency on food import can be the risk of food security even if it can bring domestic water, energy, and land savings in water scare region. Therefore, we should consider trade-off between food security and resources savings, with a holistic approach such as water-energy-food nexus, and the VWT can be suggested as relevant to the water policy of a nation (Schyns and Hoekstra, 2014), providing 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, which are raised to draw attention to the complexity of the issue and the need for a broader view in assessment. These questions are: 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 VWT network in the MENA region?

The aim of this study is to quantify the amount of VWT, and evaluate the effects on water savings and land tenure from importing crops in the MENA region. In addition, we analyze a vulnerability of the VWT in the MENA region using degree centrality index, and also evaluate influence of each Arab country on entire VWT in the MENA region through eigenvector centrality index.

2 Materials and Methods

2.1 Calculation of a virtual water trade using food trade and water footprint

The VWT represents the water embedded in international trade, and it indicates the water used in the exporting country to produce crops for export. Therefore, virtual water export in exporting country is considered as virtual water import in importing country. However, a regional VWT is different from global one; for example, virtual water import is much larger than virtual water export in each Arab country. The main factors for quantifying a VWT are trade data and water footprint (WFP, m³/ton), which is the volume of water used for producing one ton of crops, and the VWT is calculated by multiplying the trade by its associated water footprint, as follows:

$$VWT\ [n_e, n_i, \mathrm{c}, \mathrm{t}] = \mathrm{CT}\ [n_e, n_i, \mathrm{c}, \mathrm{t}] \times \mathrm{WFP}\ [n_e, c], \qquad (1)$$

in which 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 WFP of a crop is derived from the crop water requirement (m³/ha) per yield (kg/ha), as follows:

$$WFP[c] = \frac{CWR[c]}{Production\ [c]}, \qquad (2)$$

where WFP (m³/ton) is water footprint of a crop c, CWR is the crop water requirement, and Production is the yield per year. The water footprint for a crop is divided into green and blue water footprints, based on the water resources (Hoekstra and Chapagain, 2008). 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, green water footprint is related to rain-fed agriculture and blue water footprint is related to irrigation water provided by aquifers or surface bodies of water. Based on green and blue water footprints, we estimated the of four major crops—barley, maize, rice, and wheat—in the MENA region from 2000 to 2012, which was divided into green and blue water trade by footprints.

2.2 Quantification of water and land savings by importing crops using water footprint and land productivity

The import of crops in MENA region could affect the domestic water and land management in terms of water and land savings. Water saving has different meaning from virtual water import. For example, Saudi Arabia imported wheat from various exporters and virtual water import was calculated by multiplying the quantity of imported wheat with the respective water footprint of each exporter. However, water saving indicates the amount of water to produce the same quantity of imported wheat but as 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 terms of water and land savings. In this study, we consider only blue water as resource which can be saved; therefore, the national water and land savings indicated the amount of blue water and land requirements for substituting crops imported to domestic production. Thus, it was calculated as follows:

$$Water\ saving_{\ c,i} = Import_{\ c,i} \times Blue\ water\ footprint_{c,i} \qquad (3)$$

$$Lands\ saving_{\ c,i} = Import_{\ c,i} \times \frac{Lands_{c,i}}{Production_{c,i}} \qquad (4)$$

where water (or land) saving c,i indicates the amount of water (or lands)to produce the same quantity of imported crop c but as domestic production in importing country i. Import c,i indicate the amount of imported crop c in importing country i. Lands c,i and production c,i indicate the average cultivated area and production of crop c in importing country i

2.3 Analysis of a structure of virtual water trade using degree and eigenvector centrality

Understanding the VWT structure is important as quantifying the amount of import and export because VWT structure can represent whether it would be the sustainable or vulnerable. For example, if a country imports a lot of virtual water through food trade from just a few exporters, the structure of VWT in this country might be impressionable by exporters. However, if a country has connection with many exporters in VWT, it can have resilient structure for global changes. In addition, recent literature has emphasized the change in structure of the VWT in terms of a network approach (Dalin et al., 2012; Konar et al., 2012; Lee et al., 2016).

In this study, we analyzed the links of VWT network for identifying VWT structure using degree centrality, which is the number of degree incident on a given node (Freeman 1979). In addition, 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 others (Figure 1). The in-degree centrality of each Arab country was calculated because we focused more on the import of virtual water in the MENA region. An importer accompanying a high in-degree centrality has expanded connectivity with exporters, meaning that this importer could cope with an accidental disconnection from a certain exporter. A few studies that analyzed the structure of the VWT using a network-based approach have been conducted (Konar et al., 2012; Dalin et al., 2012; Lee et al., 2016). The degree centrality of the VWT is:

$$C_i = \sum_j^N VWT_{ij}/(N-1), \qquad (5)$$

where C_i is the degree centrality of country i and N is the number of total countries. VWT_{ij} is the link between the ith and jth countries.

The main concern in the MENA region is virtual water import than export. Therefore, we focused on in-degree centrality of VWT. The in-degree centrality based on the number and volume of links in VWT network, which expressed to non-scaled in-degree centrality (NSInDC) which is based on the number of links, and scaled in-degree centrality (SInDC) which is based on the volume of links (Figure 1). Through degree centrality, we analyzed the vulnerable expansion (or reduction) and robust expansion (or reduction) in the VWT network in the MENA region. Therefore, the vulnerable expansion in network indicates that the amount of flow to a node increases but the number of connection to other nodes decrease, and it is represented by high level of SInDC and low level of NSInDC. The importer who has vulnerable expansion has increased the amount of products from only a few exporters. In addition, influence of each country was analyzed using eigenvector centrality to identify influential countries who could affect the entire VWT network in the MENA region. The entire network can be affected by a few nodes, which is influential nodes, and it is important to identify these nodes for understanding and estimating the change of entire network system. An eigenvector centrality can measure important and influence of each node in the entire network, and it is related not only of own connection but also connection of other node which connects to own. Therefore, a node is more influential if it is in relation with the nodes that are, themselves, influential (Ruhnau, 2000). The eigenvector centrality assigns relative centrality to all of the nodes in the network, based on the principle that connections to high-level centrality nodes contribute more to the centrality of the nodes than equal connections to low-level centrality nodes (Ruhnau, 2000; Lee et al., 2016). Therefore, the eigenvector centrality of node is related to both the number of links to partners and their centrality (Ruhnau, 2000). Bonacich (1972) defined the centrality $c(v_i)$ of a node v_i as the positive multiple of the sum of adjacent centralities, as follows:

$$\lambda c(v_i) = \sum_{j=1}^{n} \alpha_{ij} c(v_j) \qquad \forall i. \qquad (6)$$

In matrix notation, with c $= (c(v_i), \ldots., c(v_n))$, the above equation yields

$$\mathrm{Ac} = \lambda \mathrm{c} \qquad (7)$$

This type of equation is solved using eigenvalues and eigenvectors, where A is a square matrix and is a scalar, known as the eigenvalue associated with the eigenvector c by a column vector. Eigenvector centrality is determined by calculating the principal eigenvector that has the largest eigenvalue among every eigenvector. An eigenvector of the maximal eigenvalue with only non-negative entries does exist, and we call a non-negative eigenvector ($c \geq 0$) of the maximal eigenvalue the principal eigenvector, and we call the entry $c(v_i)$ the eigenvector-centrality of node v_i (Ruhnau, 2000).

Figure 1. In- and out-degree in scaled and non-scaled network

2.4 Data collection and limitations of data availability

A main data set was international trade, and the international trade data of the study crops from 2000 to 2012 was obtained from FAOSTAT (http://www.fao.org/faostat/), as shown in Table 1. The crop with the largest amount of import was wheat, with 359.7 million ton imported by the MENA region from 2000 to 2012, followed by maize (187.2 million ton), barley (116.4 million ton), and rice (49.0 million ton). Most of the Arab countries increased the imports of the four major crops from 2000 to 2012. In particular, the largest increase was represented in Egypt, for example, the amount of the imported crops in Egypt was 11.2 million ton in 2000 and it increased to 18.0 million ton in 2012.

To quantify VWT and assess its effect on water and land savings, water footprint data of crops was essential. However, water footprint of crops is based on crop water requirement and irrigation, thus various data are required for calculating it, for example climate data, crop information, irrigation scheduling, and soil characteristics. In addition, each variable is dependent on local characteristics, thus the study for national water footprint should be executed for each country, basin, or specific area, and it was out of the scope of this study. Therefore, the estimation of water footprint was not included but we applied water footprint data set 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. In addition, the blue water footprint and land productivity for each country in the MENA region were applied to assess effects on water and land savings from importing crops. The blue water footprint for each country in the MENA region was also obtained from Mekonnen and Hoekstra (2010). Land productivity was calculated by the harvest area and crop production, which were collected from FAOSTAT (http://www.fao.org/faostat/), as shown in Table 2. Internal water resource and land area in each country were collected from World Bank (http://data.worldbank.org).

However, time scales of international trade were different from water footprint data. For example, water footprints used in this study were based on data from 1995 to 2005; however, we applied the food trade data from 2000 to 2012. Therefore, the application of average water footprint to time-series trade data can cause a false estimate of the effects of VWT. For example, the water footprint used in this study was average value for certain period (1995-2005), and the extreme climate situation could not be applied to virtual water trade analysis. Therefore, the results of VWT in this study represented generalized climate situation as a limitation.

Table 1. The amount of crops imported by the MENA region from 2000 to 2012 (FAOSTAT).

Table 2. Cultivation area and production of four major crops in the MENA region.

3 Results and Discussion

3.1 Quantification of virtual water trade in the MENA region from 2000 to 2012

The total amount of green and blue water imported by each Arab country from 2000 to 2012 reached 921.2 and 80.5 billion m³, respectively, in the MENA region, is shown in Table 3 and Figure 2. The largest volume of green water was annually imported 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 into the MENA region annually through the barley trade (approximately 8.5 billion m³/year) went to Saudi Arabia. The amount of virtual water imported through the trade of maize was 13.0 billion m³/year, with Egypt as the primary importer, importing 31% of the total imported into the MENA region.

Generally, rice is cultivated in paddy field, and the blue water footprint of rice in paddy field is larger than other cereal crops in various countries, for example, global average of blue water footprint of rice is 584 m^3/ton but wheat's is 343 m^3/ton (Chapagain and Hoekstra 2011; Mekonnen and Hoekstra 2010). Therefore, the importers of rice also import a lot of water. About 3.0 billion m^3/year of blue water were imported in the rice trade from 2000 to 2012, and Saudi Arabia, the UAE, and Iraq were the primary importers. The largest volume of virtual water imported by the MENA region was due to wheat trade. The annual amount of virtual water imported through wheat trade in the MENA region from 2000 to 2012 was approximately 42.6 billion m^3/year, but the amount of blue water was only 2.0 billion m^3/year. Over 35% of the virtual water imported through the wheat trade was imported by Egypt (15.7 billion m^3/year).

We also considered the amount of virtual water import per capita (VWIcap), which shows the differing viewpoints regarding food and water securities. If we consider only total amount of virtual water imported, the UAE might be not considered to be a significant importer because the population and area of UAE is much smaller than that of other countries such as Saudi Arabia. However, the virtual water import per capita in the UAE is larger than that of Saudi Arabia, indicating that the dependency on virtual water imported from exporters in the UAE is much more significant than in Saudi Arabia. For example, Figure 3 shows that the VWIcap was 1266.6 m^3/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 m^3/year of virtual water. The VWIcap increased significantly in Saudi Arabia and Libya from 2000 to 2012. Saudi Arabia and Libya imported about 453.4 and 497.8 m^3/cap/year, respectively, of virtual water more in 2012 than in 2000. Saudi Arabia was the second biggest importer in the MENA region, and its VWIcap was also the fifth highest in the MENA region.

We also focused on the volume of virtual water exported to the MENA region by each exporter from 2000 to 2012 (Figure 4). Through barley trade, Ukraine exported 41.1 billion m^3 of green water to the MENA region, making up 27% of the total green water imported in the MENA region through 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 through barley. In the VWT via maize, Argentina contributed 40% of the total amount of green water imported by the MENA region through maize, but the blue water imported by the MENA region was primarily from the USA. In the VWT via rice, the major virtual water exporters to the MENA region were India, Thailand, and Pakistan. In particular, 30.4 billion m^3 of blue water was imported from these countries from 2000 to 2012, which comprised 78% of the blue water imported by the MENA region through rice. Wheat was the most representative crop imported by the MENA region. The Russian Federation and the USA provided 25% (140.6 billion m^3) and 21% (111.2 billion m^3), respectively, from 2000 to 2012, of the total amount of green water imported in the MENA region through wheat, and the remaining 55% was divided among several exporters, including Australia, Canada, France, and Ukraine.

Table 3. The amount of virtual water imported by the MENA region from 2000 to 2012.

Figure 2. 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 3. Virtual water imports per capita in 2000 and 2012.

Figure 4. The amounts of green water export (GWE) and blue water export (BWE) from the primary exporters to the MENA region from 2000 to 2012.

3.2 Assessment of trade-offs between food self-sufficiency and water-lands savings through food trade in the MENA region

Food import can cause a decrease in local food production, which can be particularly a critical issue in the MENA region because Arab countries have very low food self-sufficiency and it can be problem in terms of food security. Accordingly, we applied the concept of self-sufficiency as the index of food security, which is defined as the ratio of domestic production to total consumption, and estimated water requirement of increasing 1 % self-sufficiency of study crops in comparison to average self-sufficiency from 2000 to 2012. In order to increase self-sufficiency of crop, the increase of domestic production should be accompanied, and it derives additional water and land requirement which can be issue of trade-offs between food security and water-land savings. For example, if average self-sufficiency of wheat is 70% in a specific country, the increase of 70% to 71% should accompany the increase of domestic production; therefore, water for increasing 1 % self-sufficiency indicates the water requirement for that increase of domestic production.

Table 4 shows that blue water saving by crop import in Saudi Arabia was 8.14 billion m³/year, 3.4 times larger than its internal water resources (2.40 billion m³/year). However, the land saving was 1.5 million ha/year, making up 0.9% of the total agricultural lands in Saudi Arabia, which indicates that the crop trade in Saudi Arabia has more significant benefit in terms of water resource than land resource. Egypt and the UAE were also strongly influenced by the impact of crop import on water saving. In addition, the crop import could bring a large amount of land saving; for example, about 0.24 million ha could be saved by crop import, comprising 36% of the agricultural area in Lebanon.

However, increasing food imports is also correlated to decreasing domestic food production. Accordingly, it is important to understand the trade-off between water saving and food self-sufficiency in the MENA region. In this study, we defined self-sufficiency of crops as the ratio of imported crops to total consumption, and estimated the amount of blue water footprint for increasing self-sufficiency of crops by 1% in comparison to average self-sufficiency from 2000 to 2012, as shown in Table 5. For example, the average self-sufficiency of wheat in Egypt from 2000 to 2012 was 47.64 % and 278.77 million m³ irrigation water would be required to increase self-sufficiency by 1%, in order to reach 48.64 %. The self-sufficiency of wheat in Saudi Arabia was 74.02 % and 118.11 million m³ for increasing self-sufficiency by 1%. In contrast, the self-sufficiency of wheat in Tunisia was 46.05 % but the water requirement for increasing self-sufficiency by 1% was only 3.84 million m³. As shown in results, increase of food security accompanies a lot of water requirement in the MENA region and these results can give the useful information for analyzing trade-off between food and water securities in the MENA region in terms of sustainable development. However, the saved land is now always suitable for agricultural area. Some crops are required for the specific type of land and also the productivity is different by soil. Even if we can save lands, there is the limitation for considering the land saving from this study as agricultural land savings.

Table 4. The ratio of saved water and lands to internal water resources and agricultural land area in the MENA region

Table 5. Water requirement for increasing 1 % self-sufficiency of study crops in comparison with average self-sufficiency in the MENA region from 2000 to 2012

3.3 Analysis of structural changes in virtual water trade network centering the MENA region

We analysed the degree centralities; NSInDC and SInDC from 2000 to 2012 in the MENA region and identified the countries who had the vulnerable expansion or reduction in VWT network. Figure 5 showed the NSInDC and SInDC in virtual water trade network by each country in the MENA region in 2012. If the specific country has both large NSInDC and small SInDC, this country constructs the connection with various exporters but imports small amount of virtual water. Egypt and Yemen showed that NSCInD was lower but SInDC was higher than other countries, and it indicates the intensive connectivity with a few exporters. In contrast, Saudi Arabia had larger SInDC than other countries expect for Egypt and the NSCInD was also highest in the MENA region. Accordingly, Saudi Arabia has more distributed structure of VWT. In addition, 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) smaller than UAE (0.46). In comparison to UAE, Morocco had intensive connection with less exporters than UAE.

Figure 6 showed the temporal changes of NSInDC and the SInDC during two periods (2000–2006 and 2006–2012). The number in Figure 6 represents each Arab country, for example 1 is assigned to Algeria. The shapes of each number indicate the rate of increase of in-degree centrality from 2000 to 2006 and from 2006 to 2012, respectively, in each Arab country. X-axis indicates the NSInDC and y axis indicates SInDC, therefore, if the specific country in the MENA region is located high level in x axis and low level in y axis, this country has made the connection with more exporters but decreased amount of virtual water import. Based on NSInDC and SInDC, the MENA region countries were divided into four types (I–IV). Type I countries show a robust expansion in the virtual water import, and 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 show reductions in the virtual water import with and without reduction of connectivity, respectively. In the early 2000s, most of countries in MENA region tried to expand their trade structure by increasing both the connectivity to exporters and the volume of virtual water imported. In Bahrain, Omen, Qatar, Yemen, Saudi Arabia, Lebanon, and UAE NSInDC of the VWT network increased significantly from 2000 to 2006, which means that the trade connectivity expanded. The expanded structure of VWT indicates that the Arab countries is connected to various exporters and it can be resilient structure for global changes. In particular, import of food crops is essential factor in food security in the MENA region, even if they try to increase food self-sufficiency through increasing domestic production. However. Egypt had the largest SInDC but NSInDC was located 6th in the MENA region. In 2006, Egypt expanded the connectivity in VWT network, as shown in increasing NSInDC, and Saudi Arabia also expanded the connectivity.

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 virtual water imported, but the number of exporters that linked to the Arab countries decreased or increased little from 2006 to 2012. In particular, in 2012 most of countries kept the connectivity or reduced it except for Algeria, Iraq, Libya, and UAE. For example, virtual water imported in Lebanon significantly increased from 2006 to 2012 but NSInDC decreased in 2012. Figure 7 showed the change of virtual water import in Lebanon in 2000, 2006, and 2012. In 2000 Lebanon imported most of 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 import in Lebanon. Accordingly, the structure of VWT in Lebanon was getting to a distributed network. However, the VWT in 2012 showed 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 amount of virtual water but also structure of VWT for sustainable food security in the condition of strong dependency on crop import.

These results indicate that the dependence of the MENA region on virtual water import accelerated recently with the large increase in volume of virtual water imported. However, the connectivity of the VWT in the MENA region has not increased as much as the volume of virtual water imported increased.

Figure 5. In-degree centrality of each country in the MENA region in 2012

Figure 6. Country types in the MENA region according to the rate of increase in the in-degree centrality from 2000 to 2012

Figure 7. Virtual water import from exporters to Lebanon in 2000, 2006, and 2012

We also analyzed the influence of each country on entire VWT network centering the MENA region using eigenvector centrality, as shown on Figure 8. 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, and it means that the change of 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 still were Egypt and Saudi Arabia but the influential exporters moved to Russian federation and Ukraine and Brazil.

Figure 8. Eigenvector centrality of virtual water trade network in the MENA region at 2000, 2006, and 2012

3.4 The importance and limitations of concept of virtual water 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 of the embedded water in food trade indicates water resource that is 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.

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, and it implies a strong dependency on water resource from exporting countries. Therefore, water shortages or low food production in exporting countries might cause increasing food price in the MENA region but also increasing domestic water use for increasing domestic food production.

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 trader in VWT network in the MENA region through in-degree and eigenvector centrality indices. If a country in the MENA region has low connectivity but a large amount of virtual water import, this country should revaluate their vulnerable trade structure and change the trade policy or water-food management.

However, the application of the concept of VWT is under critical discussion (Wichelns, 2010). First, water footprints bring new concepts of water management, but it is also difficult to link to operating water resource systems. Water footprint is more related to water consumption rather than water supply. We can quantify water requirement for producing food products or water saving by importing them using water footprint and VWT. However, the operation of water facilities, for example reservoir, desalination plant, and ground water pumping station, are affected by monthly rainfall and ground water level, development of technology, fertilizer usage, irrigation scheduling and system. Therefore, we need to realize that water footprint can be changed by various factors. Second, VWT could contribute to connecting water management to food security; however, food trade is affected by the scarcity or affluence of other important resource such as capital, labor, and land (Biewald et al., 2014). In particular, economic values such as 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 economic efficiency. Therefore, policy makers or resource manager in the MENA region should consider not only the effects of VWT but also the difficulty in adapting virtual water to policies for resource management.

Despite these limitations, this study attempted to analyze the VWT through various perspectives. Through the in-degree centrality of the VWT network, we identified that most countries in the MENA region increased connections with exporters and the volume of virtual water imported between 2000 and 2006. However, most countries increased the volume of virtual water imported without increasing the expansion of connections between 2006 and 2012. These results could underscore the fact that the VWT structure has not recently increased in robustness. We believe that virtual water has a role in achieving sustainable water, land, and food security, even if there are limitations and difficulties in applying the virtual water concept.

4. Conclusions

The VWT, importing water in virtual form, could be a major water portfolio that dominates water management in the water-scarce countries of the MENA region. Since the virtual water concept was introduced, 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 virtual water imported is regarded as the most important factor in determining water and food security, and the results of water and land savings by crop import in the MENA region could show the importance of international trade.

In particular, the interlinkages across key natural resource sectors and improved efficiency of production is considered a win-win strategy for environmental sustainability, whether 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 inter-linked: decisions made in one sector typically impact the other sectors (Mohtar and Daher, 2014). Therefore, we believe that virtual water can be useful connector among water, food, and land in Nexus system. In addition, VWT and water-land savings by trade in this study can be used for supporting decision through Nexus system.

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

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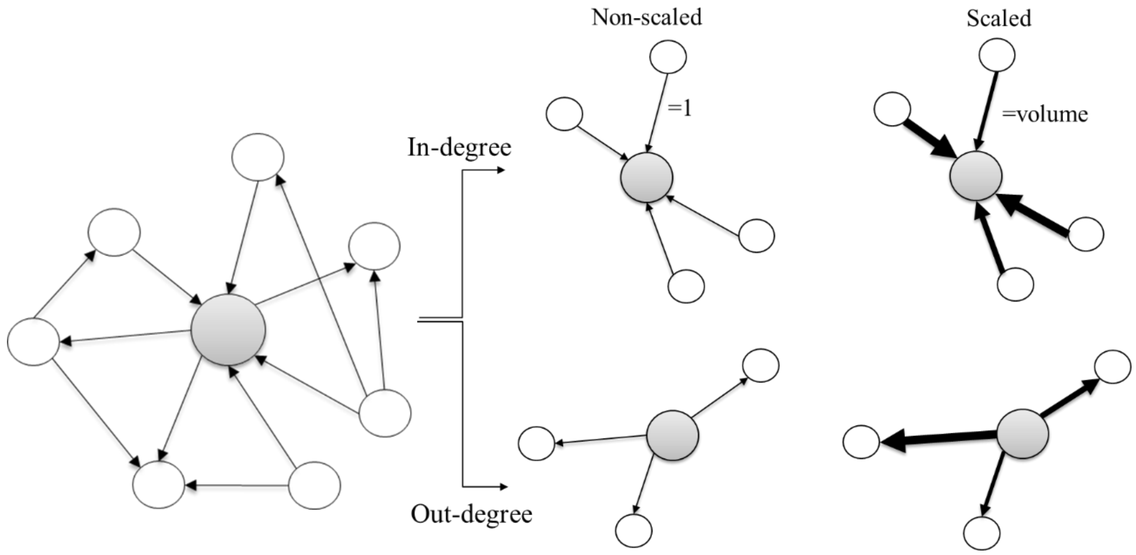
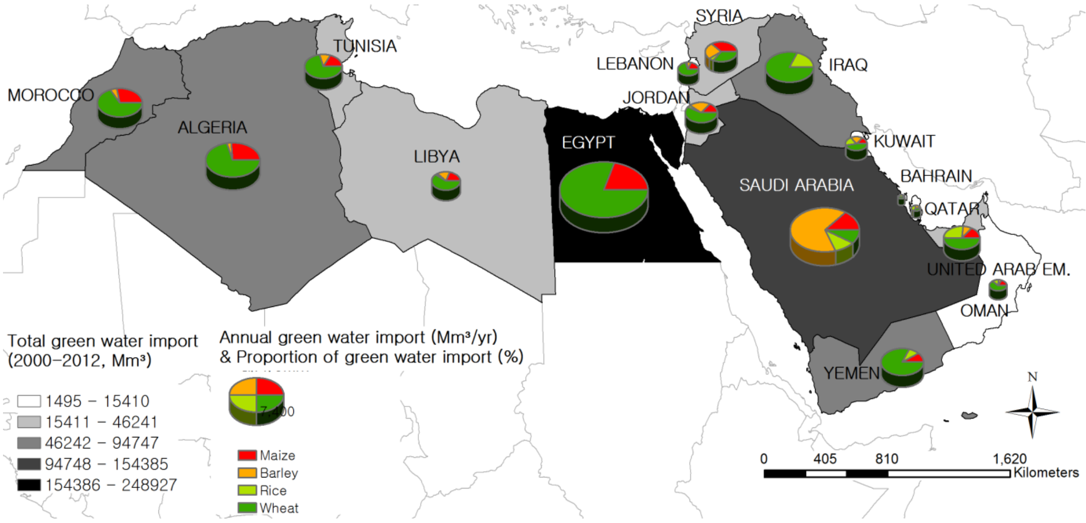
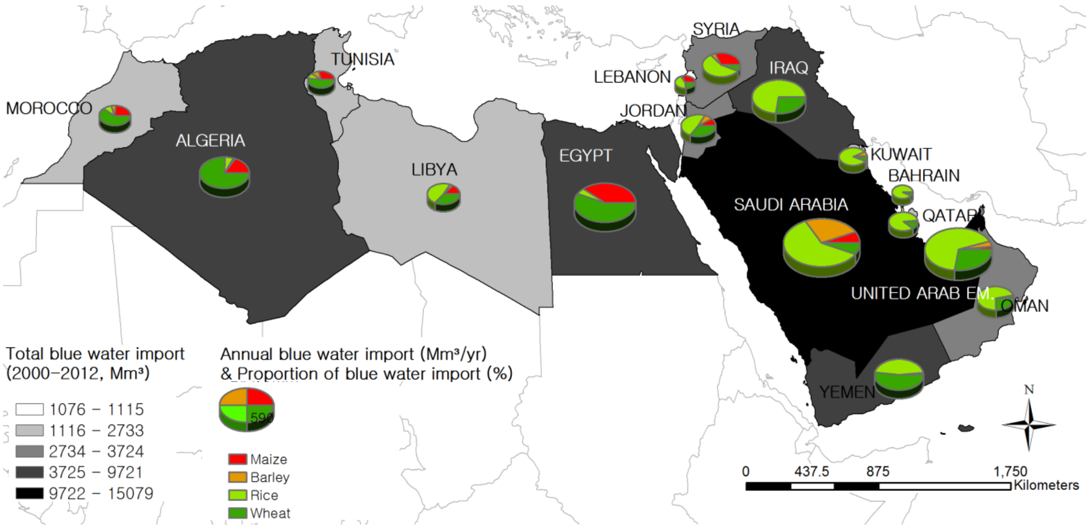


Figure 2. In- and out-degree in scaled and non-scaled network



(a) Green water imports



(b) Blue water imports

Figure 2. 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**.**

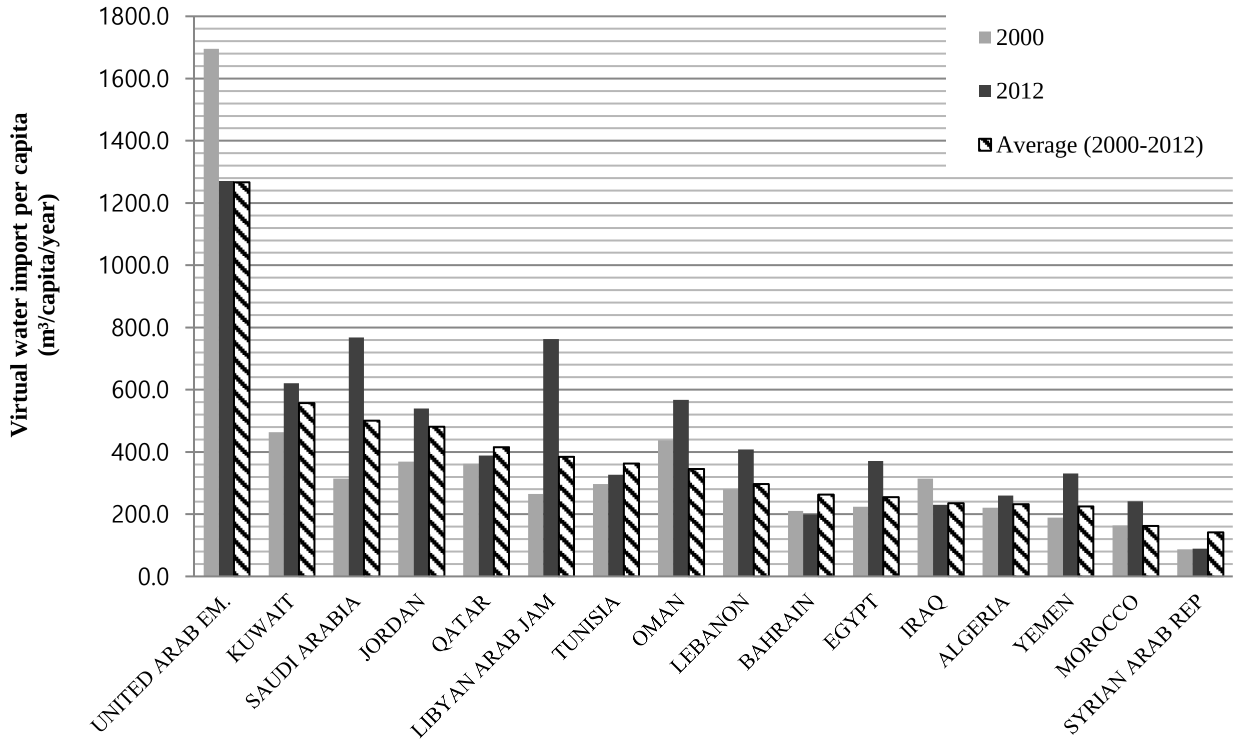
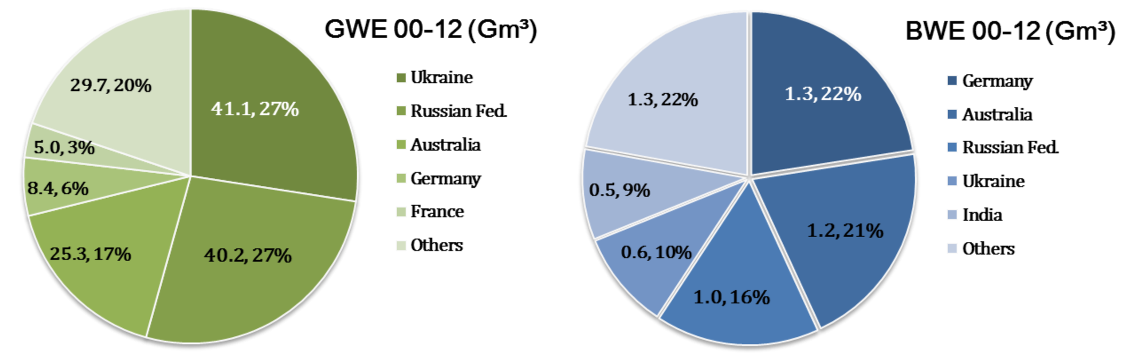
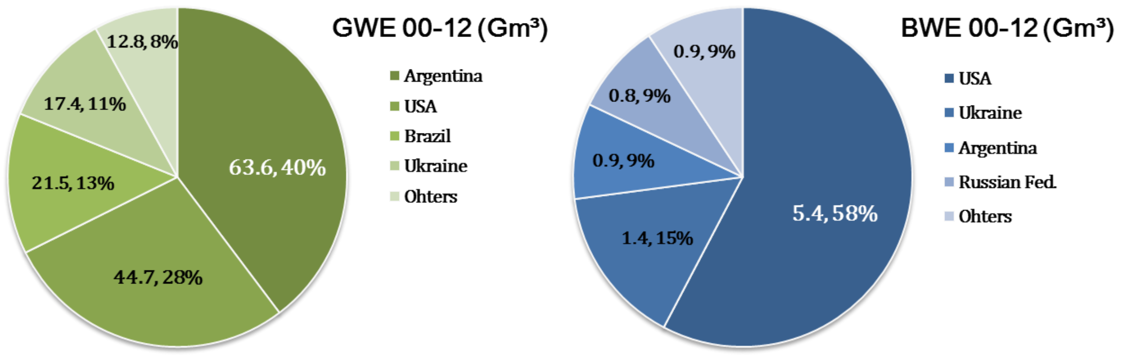


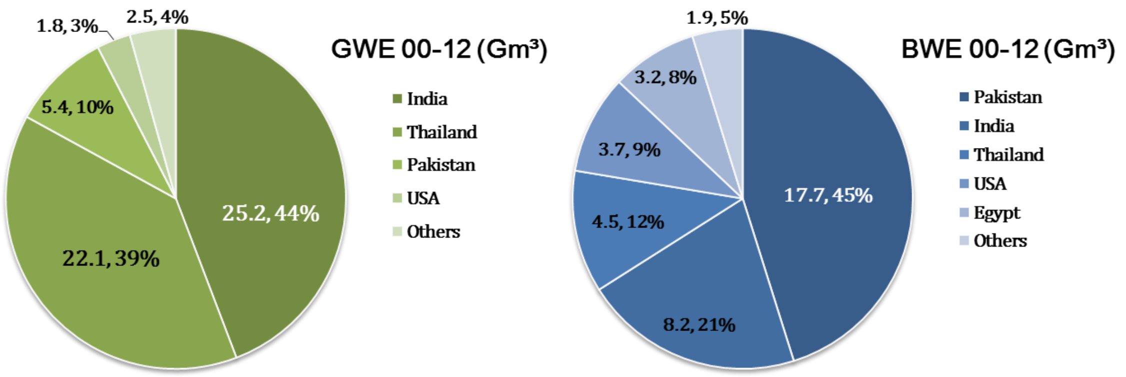
Figure 3. Virtual water import per capita in 2000 and 2012.



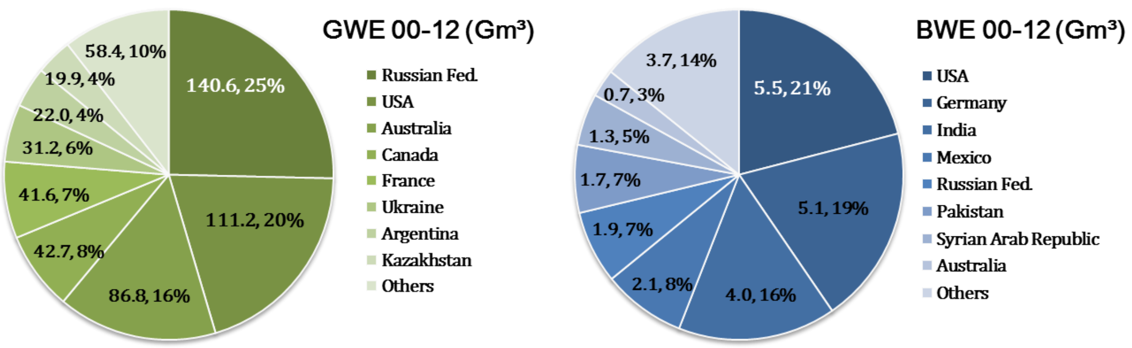
(a) Barley



(b) Maize



(c) Rice



(d) Wheat

Figure 4. The amounts of green water export (GWE) and blue water export (BWE) from the primary exporters to the MENA region from 2000 to 2012

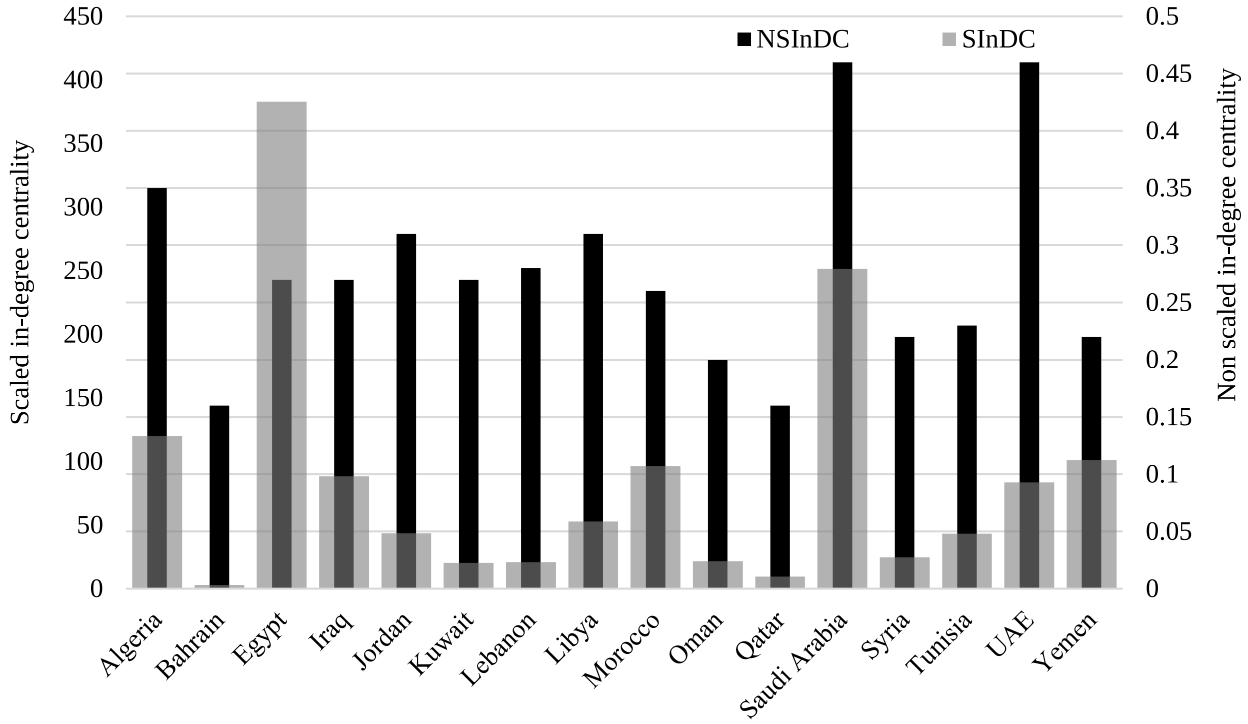


Figure 5. In-degree centrality of each country in the MENA region in 2012

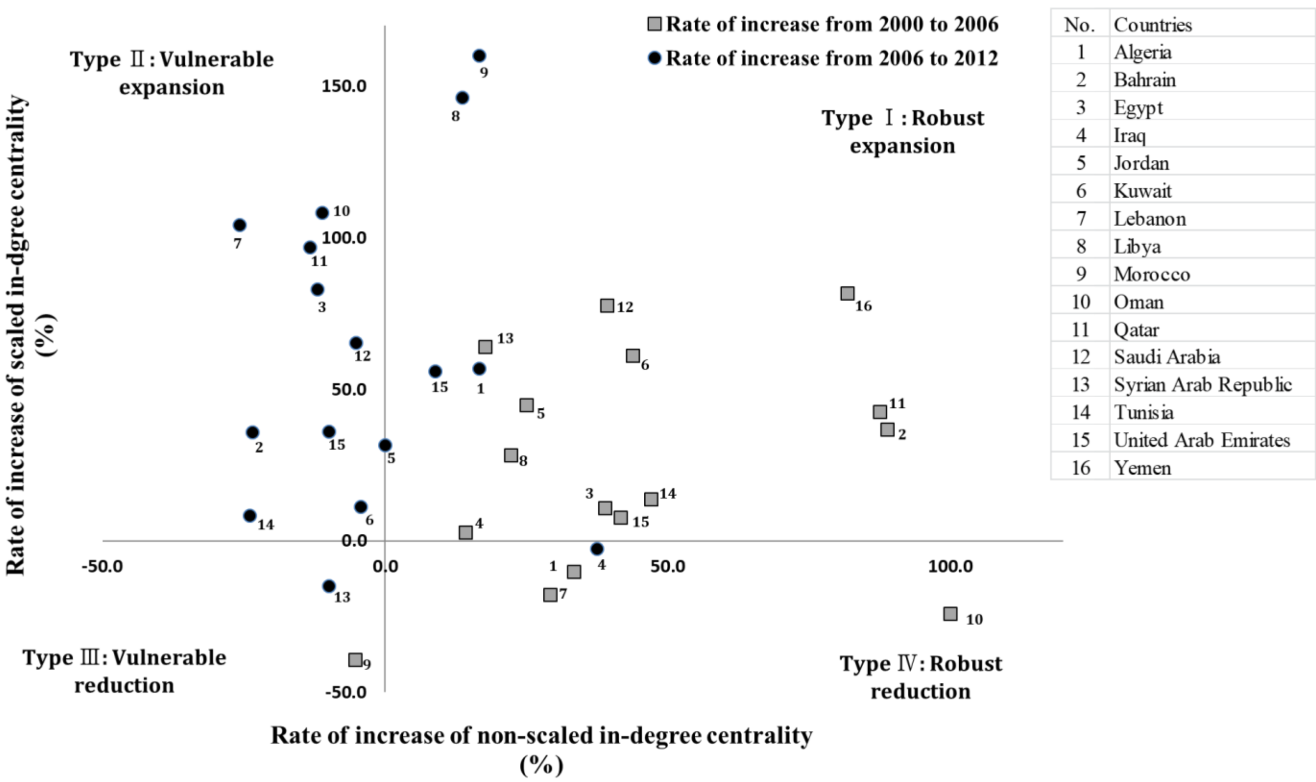
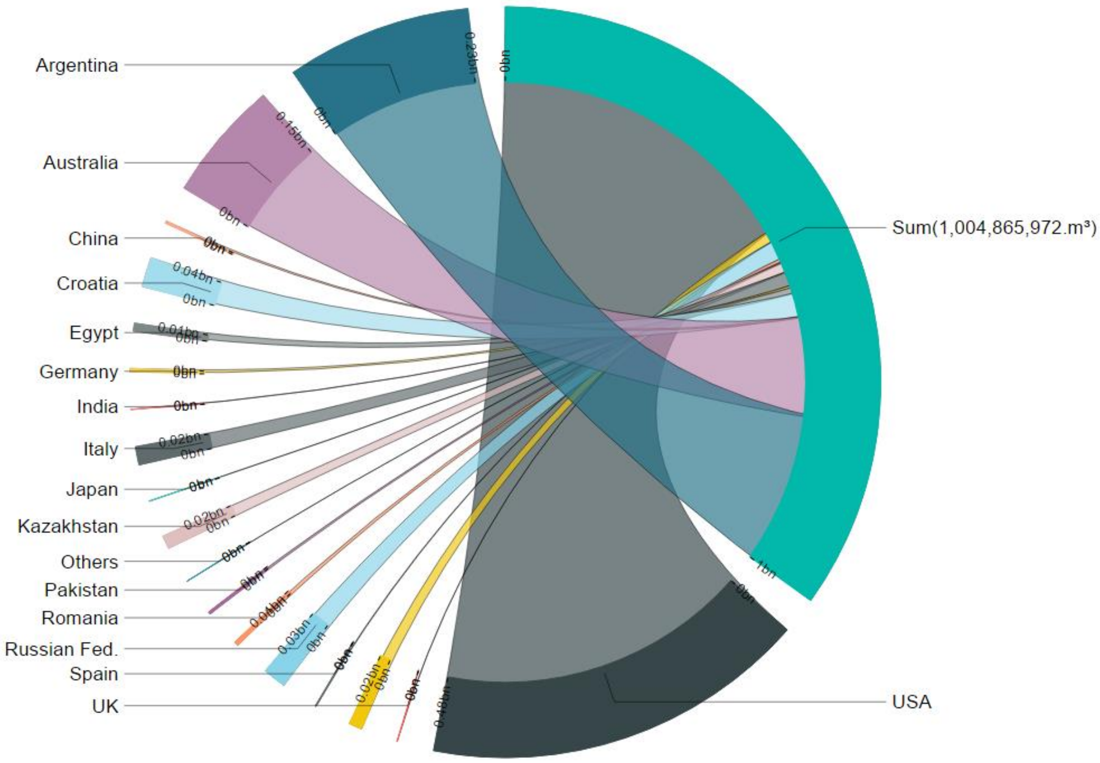
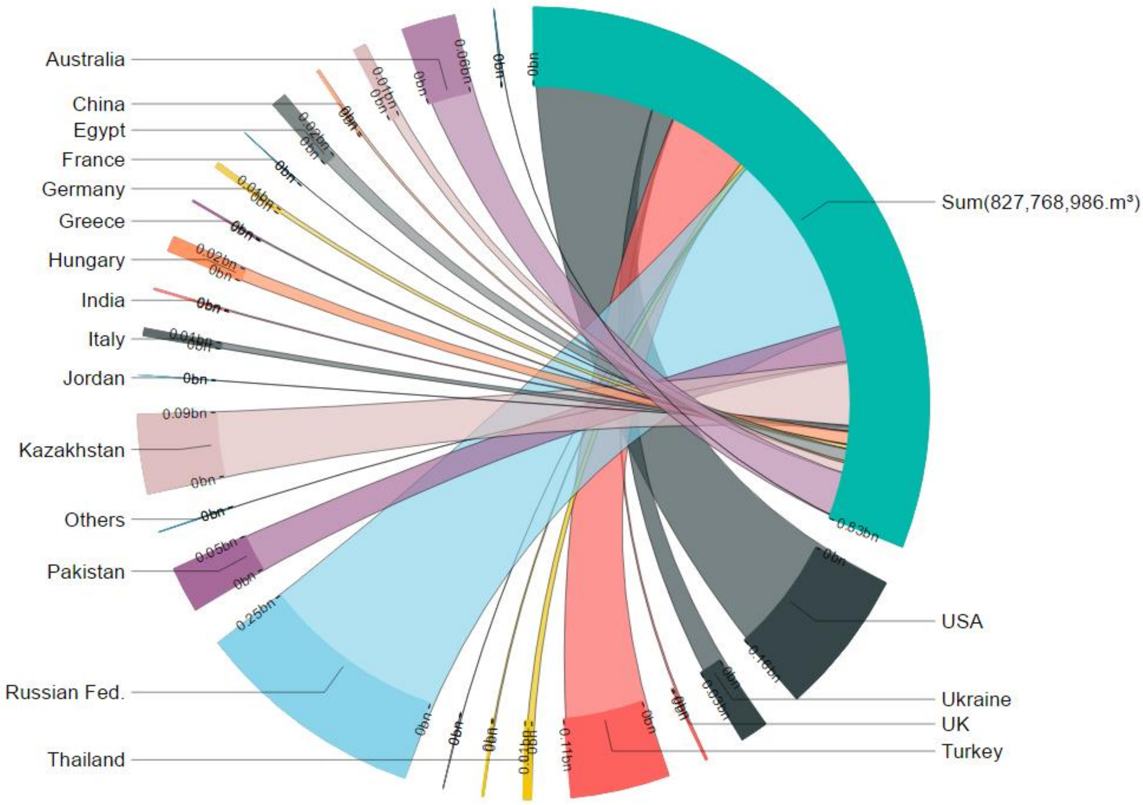


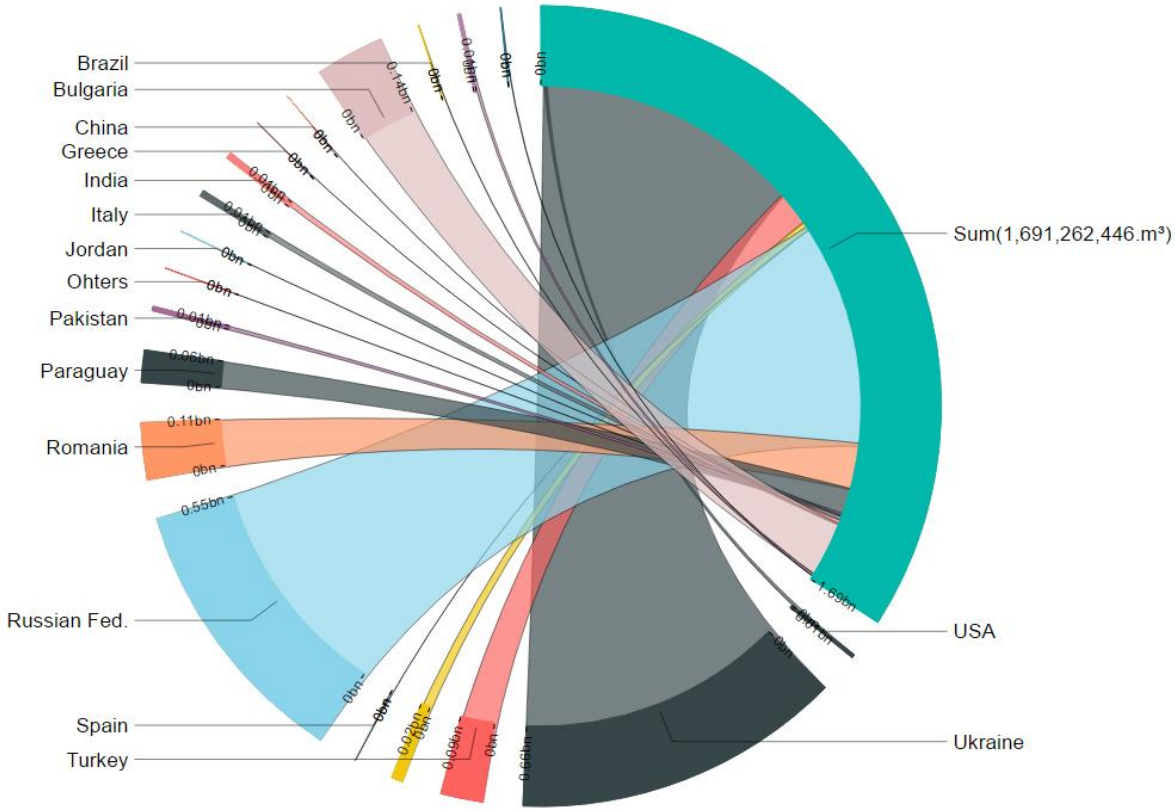
Figure 6. Country types in the MENA region according to the rate of increase in the in-degree centrality from 2000 to 2012


Argentina
Australia
China
Croatia
Egypt
Germany
India
Italy
Japan
Kazakhstan
Others
Pakistan
Romania
Russian Fed.
Spain
UK
Sum(1,004,865,972.m³)
USA

(a) 2000


Australia
China
Egypt
France
Germany
Greece
Hungary
India
Italy
Jordan
Kazakhstan
Others
Pakistan
Russian Fed.
Thailand
Sum(827,768,986.m³)
USA
Ukraine
UK
Turkey

(b) 2006



(c) 2012

Figure 7. Virtual water import from exporters to Lebanon in 2000, 2006, and 2012.
(bn indicates billion m³)

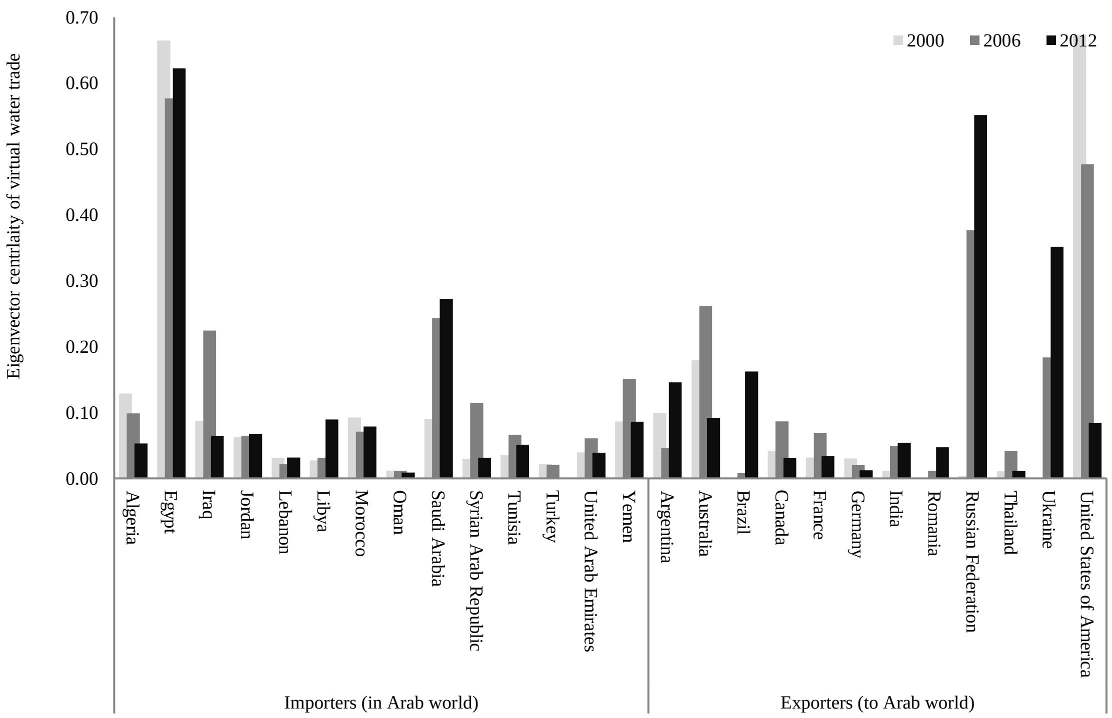


Figure 8. Eigenvector centrality of virtual water trade network in the MENA region at 2000, 2006, and 2012

Table 1. The amount of crops imported by the MENA region from 2000 to 2012

Importers in the MENA region	Crop import from 2000 to 2012							
	Total import (10^6 ton)				Annual import (1000 ton/year)			
	Barley	**Maize**	**Wheat**	**Rice**	**Barley**	**Maize**	**Wheat**	**Rice**
ALGERIA	3.04	27.46	69.73	0.61	234	2,113	5,364	47
BAHRAIN	0.00	0.09	0.52	0.62	0	7	40	48
EGYPT	0.32	65.96	107.85	0.60	25	5,074	8,296	46
IRAQ	0.25	0.23	33.10	9.65	35	19	2,546	742
JORDAN	6.34	5.02	10.30	1.79	488	386	793	137
KUWAIT	2.32	1.75	3.70	2.23	178	134	285	171
LEBANON	0.64	3.77	4.78	0.60	49	290	367	46
LIBYA	2.94	5.58	10.45	1.59	226	429	804	123
MOROCCO	5.10	18.81	38.93	0.17	393	1,447	2,994	13
OMAN	0.47	1.29	3.75	1.54	36	100	288	119
QATAR	0.43	0.05	0.62	1.14	33	4	48	87
SAUDI ARABIA	81.29	20.80	9.11	13.12	6,253	1,600	701	1,009
SYRIA	5.11	17.15	5.91	2.62	393	1,319	455	202
TUNISIA	5.30	9.59	19.84	0.23	407	738	1,526	17
UAE	2.80	5.20	13.83	8.88	215	400	1,064	683
YEMEN	0.02	4.47	27.26	3.63	3	344	2,097	279
Total	116.4	187.2	359.7	49.0	8,968	14,404	27,668	3,769

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

Table 2 Cultivation area and production of four major crops in the MENA region.

Importers	Average cultivation area from 2000 to 2012 (ha/year)			
in the MENA region	**Barley**	**Maize**	**Wheat**	**Rice**
ALGERIA	760,545	308	1,658,197	-
EGYPT	68,103	876,153	1,180,644	625,626
IRAQ	914,074	128,842	1,451,219	85,182
JORDAN	31,158	947	20,116	-
KUWAIT	1,058	290	173	-
LEBANON	13,515	949	45,380	-
LIBYA	191,641	1,356	165,469	-
MOROCCO	2,118,032	226903	2,910,977	5,876
OMAN	1,002	-	426	-
QATAR	947	94	15	-
SAUDI ARABIA	12,279	16,689	374,414	-
SYRIA	1,313,101	53,405	1,667,229	-
TUNISIA	385,189	-	722,038	-
UAE	14	144	18	-
YEMEN	39,276	40,774	110,138	-
Importers	**Average production from 2000 to 2012 (ton/year)**			
in the MENA region	**Barley**	**Maize**	**Wheat**	**Rice**
ALGERIA	1,049,710	1,128	2,313,464	-
EGYPT	134,034	6,812,845	7,549,253	6,023,684
IRAQ	751,099	307,682	2,009,972	232,040
JORDAN	22,757	17,514	23,379	-
KUWAIT	2,191	5,855	345	-
LEBANON	24,834	3,579	126,623	-
LIBYA	94,107	2,997	128,149	-
MOROCCO	1,867,670	159,127	4,200,596	36,936
OMAN	3,027	-	1,432	-
QATAR	2,841	1,329	34	-
SAUDI ARABIA	68,366	86,181	1,997,598	-
SYRIA	817,609	211,675	4,008,420	-
TUNISIA	411,431	-	1,302,438	-
UAE	111	2,931	74	-
YEMEN	32,248	57,329	173,437	-

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

Table 3 The amount of virtual water imported by the MENA region from 2000 to 2012.

Importers in the MENA region	Green water import (10^6 m^3/year)				Blue water import (10^6 m^3/year)			
	Barley	**Maize**	**Wheat**	**Rice**	**Barley**	**Maize**	**Wheat**	**Rice**
ALGERIA	242.0	1,883.6	5,104.8	57.8	7.8	76.6	371.1	33.5
BAHRAIN	0.4	7.5	62.7	44.4	0.2	0.3	7.1	78.2
EGYPT	37.3	3,798.4	15,254.1	58.4	1.1	295.6	418.6	32.5
IRAQ	33.2	16.7	4,645.8	1,027.8	2.2	1.3	153.9	404.8
JORDAN	656.8	364.2	1,483.9	81.2	20.8	20.8	84.5	115.0
KUWAIT	257.0	159.1	557.7	211.6	9.7	2.3	10.2	138.1
LEBANON	84.7	211.0	749.5	30.0	2.3	25.6	18.9	36.0
LIBYA	359.6	408.9	1,245.4	56.0	8.4	26.8	75.3	99.7
MOROCCO	318.6	1,383.2	3,345.0	8.9	12.1	46.1	118.8	20.4
OMAN	52.7	123.2	470.8	107.6	5.4	4.1	67.8	201.3
QATAR	50.9	6.4	76.4	77.6	2.4	0.3	19.1	146.9
SAUDI ARABIA	8,154.5	1,521.4	974.0	1,225.9	324.3	68.9	70.8	696.0
SYRIA	556.4	947.3	900.0	120.8	12.8	90.2	17.8	165.6
TUNISIA	409.8	611.7	2,507.7	27.8	16.0	40.7	73.9	11.6
UAE	315.7	465.8	1,671.8	859.5	28.5	14.3	249.3	612.5
YEMEN	3.1	406.1	3,597.3	392.7	1.6	8.2	247.3	220.8
Total	11,532.9	12,314.5	42,646.9	4,388.0	455.5	722.1	2,004.4	3,012.9

Table 4 The ratio of saved blue water and lands to internal water resources and agricultural land area in the MENA region

Importers	**Internal water resources*** (10^9 m^3/year)	**National blue water saving** (10^9 m^3/year)	**Ratio of blue water saving** (%)	**Agricultural land*** (1000 ha/year)	**National land saving**** (1000 ha/year)	**Ratio of land saving** (%)
ALGERIA	11.25	0.56	5.0	41432	4902	11.8
EGYPT	1.80	13.05	725.0	3761	1964	52.2
IRAQ	35.20	12.17	34.6	9230	2398	26.0
JORDAN	0.68	1.02	150.0	1057	1531	144.8
KUWAIT	-	1.14	-	154	229	148.7
LEBANON	4.80	0.06	1.3	658	238	36.2
LIBYA	0.70	1.73	247.1	15355	1704	11.1
MOROCCO	29.00	5.39	18.6	30401	6001	19.7
OMAN	1.40	0.69	49.3	1469	100	6.8
QATAR	0.06	0.17	283.3	68	32	47.1
SAUDI ARABIA	2.40	8.14	339.2	173295	1501	0.9
SYRIA	7.13	2.36	33.1	13921	1417	10.2
TUNISIA	4.20	0.21	5.0	9943	1288	13.0
UAE	0.15	0.82	546.7	382	387	101.3
YEMEN	2.10	6.05	288.1	23546	1656	7.0

* World Bank 2014

** Land saving considered barley, maize, and wheat except for rice because of lack of data.

Table 5 Average self-sufficiency and water requirement for increasing 1 % self-sufficiency of study crops in the MENA region from 2000 to 2012

Importers	Average self-sufficiency from 2000 to 2012 (%)			Additional irrigation water requirement (10^6 m³)		
	Barley	**Maize**	**Wheat**	**Barley**	**Maize**	**Wheat**
ALGERIA	81.77%	0.05%	30.13%	5.88	1.74	7.27
EGYPT	84.28%	57.31%	47.64%	18.31	307.44	278.77
IRAQ	95.55%	94.18%	44.12%	983.99	122.93	233.96
JORDAN	4.46%	4.34%	2.86%	1.73	0.35	8.40
KUWAIT	1.22%	4.19%	0.12%	4.16	0.31	6.60
LEBANON	33.63%	1.22%	25.65%	0.00	0.04	0.65
LIBYA	29.40%	0.69%	13.75%	8.32	0.36	16.87
MOROCCO	82.62%	9.91%	58.39%	10.88	57.38	43.33
OMAN	7.76%	0.00%	0.49%	1.00	0.08	5.70
QATAR	7.93%	24.94%	0.07%	0.67	0.04	0.79
SAUDI ARABIA	1.08%	5.11%	74.02%	51.64	22.81	118.11
SYRIA	67.54%	13.83%	89.81%	1.60	28.28	213.67
TUNISIA	50.27%	0.00%	46.05%	1.26	0.61	3.84
UAE	0.05%	0.73%	0.01%	0.17	0.33	5.46
YEMEN	91.49%	14.28%	7.64%	-	13.98	58.54