Evaluation of water shortage crisis in the Middle East and possible remedies

Omid Bozorg-Haddad, Babak Zolghadr-Asli, Parisa Sarzaeim, Mahyar Aboutalebi, Xuefeng Chu and Hugo A. Loáiciga

ABSTRACT

Water resources in the Middle East region are becoming scarce, while millions of people already do not have access to adequate water for drinking and sanitary purposes. Water resources depletion has become a significant problem in this region that is likely to worsen. Current research by remote sensing analysis indicates a descending trend of water storage in the Middle East region, where agriculture plays a crucial role in socio-economic life. This study introduces an approach quantifying water depletion in the Middle Eastern countries, which are being challenged in the management of their water resources. Furthermore, this paper presents results of a survey assessing the status of water use and supply in Middle Eastern countries and outlines some potential remedies. Specifically, Iran's water use is evaluated and compared with its neighbors'. The water equivalent anomaly (WEA) and total water storage (TWS) depletion are two indexes of water scarcity calculated for Middle Eastern countries surveyed herein. Our analysis reveals that Lebanon, Syria, Iraq, and Iran are countries with very negative water scarcity indexes. These estimates prove that international cooperation is needed to manage available regional water resources and reverse depletion of natural water sources. It is demonstrated herein that virtual water trade can help remediate regional water shortage in Middle Eastern countries.

Key words | GRACE satellite, Middle East region, water crisis, water equivalent anomaly, water resources management, water scarcity

Omid Bozorg-Haddad (corresponding author)
Babak Zolghadr-Asli
Parisa Sarzaeim
Mahyar Aboutalebi
Department of Irrigation & Reclamation Engineering, Faculty of Agricultural Engineering & Technology, College of Agriculture & Natural Resources,
University of Tehran,
3158777871 Karaj,
Iran
E-mail: *obhaddad@ut.ac.ir*

Xuefeng Chu
Department of Civil & Environmental Engineering,
North Dakota State University,
Department 2470, Fargo, ND,
USA

Hugo A. Loáiciga
Department of Geography,
University of California,
Santa Barbara, CA 93016-4060,
USA

INTRODUCTION

Despite the technological advancements of the modern era, water-related problems remains a dauting challenge of the 21st century (Kanakoudis *et al.* 2017a). Reportedly, it has been estimated that one-fifth of the world's population is facing water scarcity. Population growth and climate change could further complicate this looming water-related challenge. While some regions have begun to tackle their water-related problems (e.g., North Africa (Kummu *et al.* 2010), South Africa (Binns *et al.* 2001), and the Mediterranean region (Kanakoudis *et al.* 2017b)), the Middle East is lagging behind in this respect.

The Middle East is a strategic transcontinental region. It lies at the point where Eurasia, Africa, and the Indian Ocean intersect, and has a historic legacy dating back to the invention of agriculture. The term 'Middle East' appears to have originated in the mid-19th century, and its meaning morphed through the 20th century (Davison 1960). From a historic perspective, the Middle East is known as the cradle of civilization due to the formation of two early communities near the Nile River in Egypt and Tigris-Euphrates in Iraq (Macklin & Lewin 2015). Geographically, the Middle East is a region in western Asia, which stretches

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from Egypt to Iran. Specifically, the countries in the Middle East include Bahrain (BHR), Cyprus (CYP), Egypt (EGY), Iran (IRN), Iraq (IRQ), Israel (ISR), Jordan (JOR), Kuwait (KWT), Lebanon (LBN), Oman (OMN), Qatar (QTR), Saudi Arabia (SAU), Syria (SYR), Turkey (TUR), United Arab Emirates (UAE), and Yemen (YEM).

The Middle East region is usually associated with being the cradle of religions, harboring ostensible landmarks, enduring persistent warfare, and possessing vast petroleum reserves (Wolfsfeld 1997). Yet, concerning the management of its water resources, this region may be on the verge of a tectonic shift in view that a water crisis is underway (Starr 1991; Sowers *et al.* 2011).

Presumably, the Middle East region is already considered by many water experts as a water-stressed region (Madani 2014). Based on the *local* evidence and studies (e.g., Gleick 1994; Kliot 2005; Dalin *et al.* 2017; Ashraf *et al.* 2019), there are undeniable hints of a looming water scarcity in general; yet, not much is known about the true magnitude and the extensiveness of this alleged environmental challenge. This worsening water crisis, however, could be amplified into a calamity for many countries and could have wide-ranging repercussions. Several factors coalesce to cast a shadow on the water future for many countries in the Middle East region. Those factors, for instance, include climate change projections of diminishing blue water (i.e., fresh surface water and groundwater of natural origin), population growth, and the rise of per capita water use.

To put the magnitude of this alleged crisis into proper context, one should bear in mind that the Middle East is a semi-arid to arid region. That is, it features predominantly a hot and dry climate with relatively low precipitation. In terms of water supply and demand, these are conflicting conditions for water resources management. For instance, water storage in the Tigris and Euphrates River Basin, located centrally in the Middle East, is decreasing approximately at a rate of 27 mm annually (Voss *et al.* 2013).

The average annual available water in the Middle East equals 1,200 cubic meters (m^3) per person, about six times less than the world average which is 7,000 m^3 per capita (Lorenzo & Vega 2010). In order to have a proper context for analyzing these data one should note that while the worldwide threshold of water scarcity is 1,000 m^3/person/year, annual per capita water availability less than 1,700 m^3 implies a water-stressed region (UNDP 2006; Siddiqi & Anadon 2011). Furthermore, an annual water supply less than 500 m^3 per person signifies an absolute water scarcity in a region. According to the projections for the Middle East region, the water availability may fall under 1,000 m^3/person/year by 2050 (Rijsberman 2006).

As for the demand side of the water resources, the Middle East uses more than 75% of its freshwater resources and this situation could be dramatically exacerbated by population growth (Zdanowski 2014). As expected, population growth induces higher demands on available water resources in the Middle East's countries, creating severe water-supply challenges. Furthermore, it is estimated that 85% of the water use in the Middle East is used for irrigation (World Bank 2007). Projected population growth in the region most likely will increase the agricultural water use for food production. Decreased water resources and population growth in the Middle East raise the specter of chronic water scarcity and its multiplicity of adverse impacts. Thus, assessment of water shortage, depletion, and identification of effective solutions are needed to mitigate the water stresses in the Middle East.

The status quo does not depict a favorable situation in terms of water resources conditions in the Middle East; furthermore, the projected changes in hydro-climatic variables reinforce the struggle to cope with the region's water resources in the future. Predictions of climatic change suggest the Middle East will face a 5 to 25% decrease in annual precipitation. In Iran, for instance, this decline in the annual precipitation is projected to be 20 to 25% less than the current value (Ragab & Prudhomme 2002). Anthropogenic activities may also make the situation more challenging for water resources management. It is estimated, for instance, that groundwater resources reduction is occurring in Iran with a mass loss rate of 25 ± 3 Gt/year (1 Gt = 1 km^3 of freshwater) (Joodaki *et al.* 2014).

An assessment of water shortage is necessary to quantify the availability of regional water sources and their likely changes due to climate change, and to assess the current and future water uses needed to maintain economic and environmental quality (Oki & Kanae 2006). In addition, alternative water sources such as seawater desalination, water recycling and reuse, and the need for stricter environmental protection standards should also be taken into account in such assessments. However, evaluating these factors can be difficult, and sometimes even impossible, due to the lack of the pertinent information, monitoring systems, and databases. The following questions are often raised concerning the Middle East's water resources status: Is water scarcity threatening the Middle East? If such a threat escalates regionally, which of the Middle Eastern countries are more vulnerable? Lastly, could a future water crisis in the Middle East region be prevented or remediated? This paper's key objectives are to provide a numeric-based perspective to assess the water depletion rates in the Middle East countries by means of the water equivalent anomalies (WEAs), and to identify possible remedies associated with virtual water trade to mitigate the water depletion in the Middle East.

MATERIALS AND METHODS

Data sources

The water-use data availability varies for the selected countries due to the reluctance of some countries to reveal accurate pertinent information. The remote sensing data from the Gravity Recovery and Climate Experiment (GRACE) satellite system, however, can provide estimates of the variations in the water equivalent over large terrestrial environments. The GRACE twin satellites, which were launched in March 2002, can make precise measurements of changes in the gravitational field caused by fluctuating water masses within regions. The GRACE products have a coarse resolution; yet, the accuracy is acceptable for assessing the regional-scale changes in water availability, induced by water movement and water depletion. In this study, the GRACE satellite imageries are used to estimate the water equivalent anomaly (WEA).

The WEA involves real-time monitoring of the total water storage (TWS) of a region. It is determined by satellite measurements of the changes in the gravitation field in the region. The WEA can be estimated by the deviation of the TWS over the period of measurement from the long-term average TWS in the region. The deviation is expressed as a depth of water over the region of measurement (Landerer & Swenson 2012).

Methodology

Surface water and groundwater are the major water resources in the Middle East region. Note that other sources, such as glaciers, are negligible in this area. The GRACE satellite data are utilized in this study to determine the total water change in the Middle East region. The observed changes are directly proportional to the changes in mass near the Earth's surface, which reflect the changes in total water storage over a given period (Scanlon et al. 2015).

The water equivalent within a region is expressed as the depth of water over the region. The depth represents the volume of water per unit surface area, including land and water surfaces, whereas the water includes surface water and groundwater bodies. Thus, a 1 mm water equivalent over an area of 10^6 km^2 equals 1 km^3 of water in the area. Given the previous warning of a reduction of water storage in the region under consideration (e.g., Bou-Zeid & El-Fadel 2002; Chenoweth et al. 2011), this study aims to use a long-term WEA from GRACE (2002–2015) extracted for each of the Middle Eastern countries. The WEA analysis elucidates trends with the purpose of assessing the pattern of water resources reduction across countries.

Note that the term 'water crisis' implies a condition of water availability and water use that undermine a locality's capacity to achieve the criteria of human, social, and environmental well-being specified in the definition of water security.

CASE STUDY

The GRACE data between 2002 and 2015 were used to estimate the share of total water depletion in the Middle East countries. Figure 1 shows the geographical locations of the Middle East countries, for which GRACE data are extracted and analyzed. Moreover, the water depletion with emphasis in Iran and its neighbors (Afghanistan, Armenia, Azerbaijan, Iraq, Pakistan, Turkey, and Turkmenistan) is assessed by using the WEA products from the GRACE data. Figure 2 depicts the WEA in Iran and its neighbors for the period of 2002–2015. It can be observed that the most pronounced negative WEA occurred in northeastern Iraq, northern Iran,

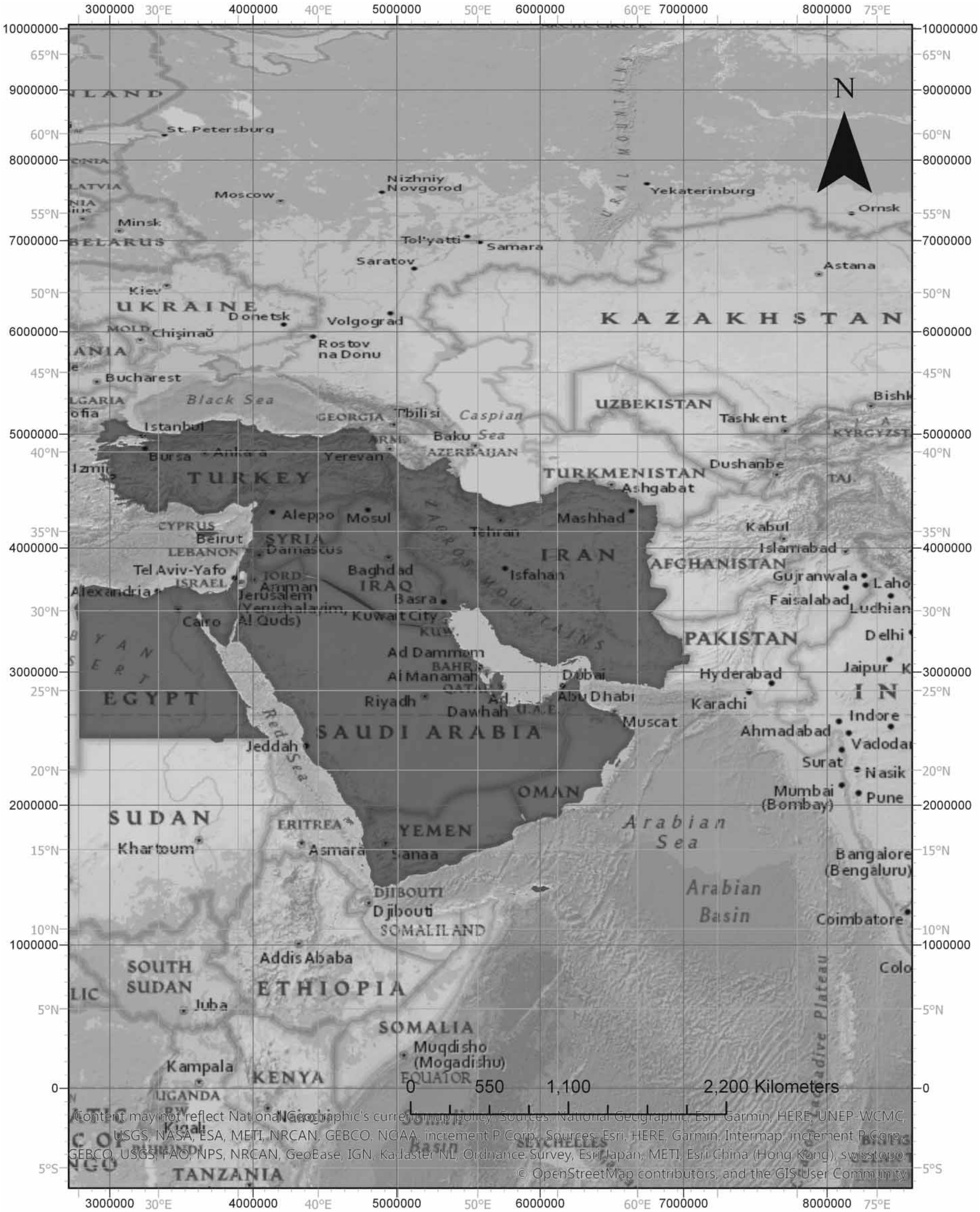

Figure 1 | Geographical locations of the Middle East countries (highlighted with the darker layer).

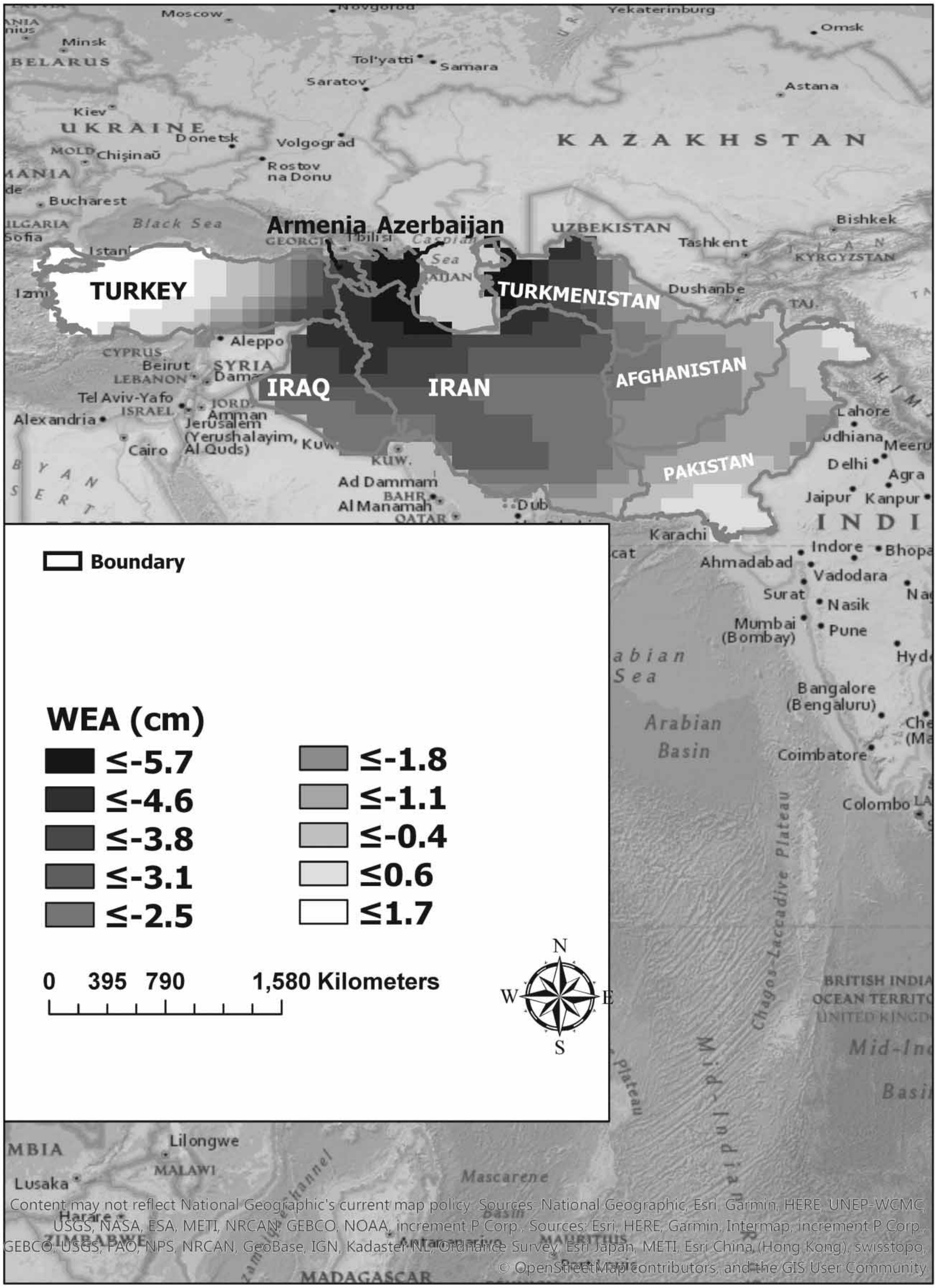

Figure 2 | WEA in 2002–2015 in Iran and its immediate neighbors.

all of Armenia, and Azerbaijan, eastern Turkey, and western Turkmenistan.

RESULTS AND DISCUSSION

WEA assessment in the Middle Eastern countries

Most Middle Eastern countries feature an oil-oriented economy, natural water scarcity, and fast-growing population. Figure 3 summarizes the Middle East's key demographic (population) and water-resources change (expressed as the WEA) indicators in 2015. Figure 3 indicates that all the Middle Eastern countries have negative WEAs. This means that in 2015 all the Middle Eastern countries were compelled to tap into their non-renewable water resources or resort to artificial water sources (e.g., seawater desalination and water recycling, although the cost of such operations may be relatively high in some cases).

From 2002 through 2015, the average annual WEA in the Middle East was −1.86 cm and all the Middle Eastern countries exhibited negative WEA in this time period; yet, the measured WEA differed among them. For instance, Lebanon scored the most negative average annual WEA (−14.26), implying a declining water storage in the future. In addition, Syria (−10.25), Iraq (−10.17), and Iran (−9.76) are other countries with very negative WEAs. On the other hand, Oman, with an average annual WEA of −0.30, manages to control the over-exploitation of its water resources, mitigating some of the adverse impacts on its water balance. The United Arabian Emirates (−0.53), Qatar (−0.88), and Saudi Arabia (−0.94) are among the best performers based on the WEA in 2003–2015. The smaller negative WEAs for these three countries should not be a relief for their authorities, however, given that their WEAs reflect a declining available water trend as their population grows.

Figure 4 shows linear trends fitted to the Middle Eastern countries' WEAs in the period of 2003–2015.

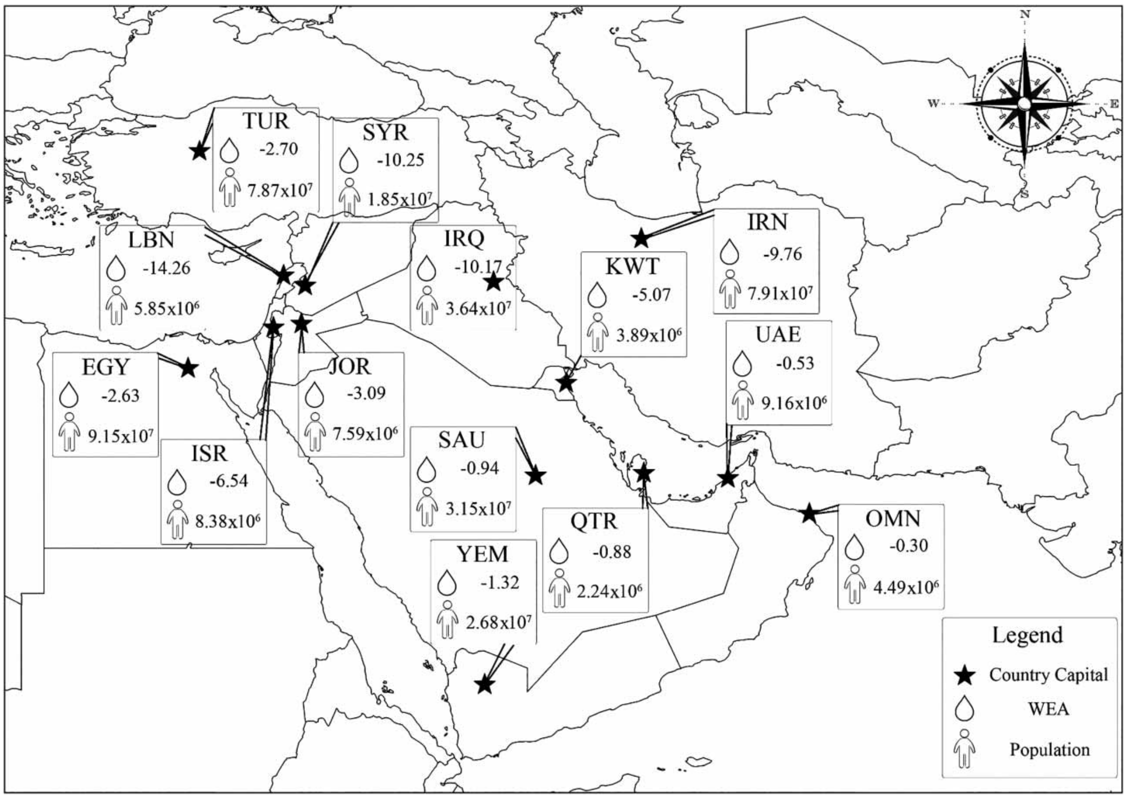

Figure 3 | Middle East countries' water equivalent anomalies (WEA, cm/year) and population in 2015 (the population data are obtained from the World Bank's database (http://data.worldbank.org)).

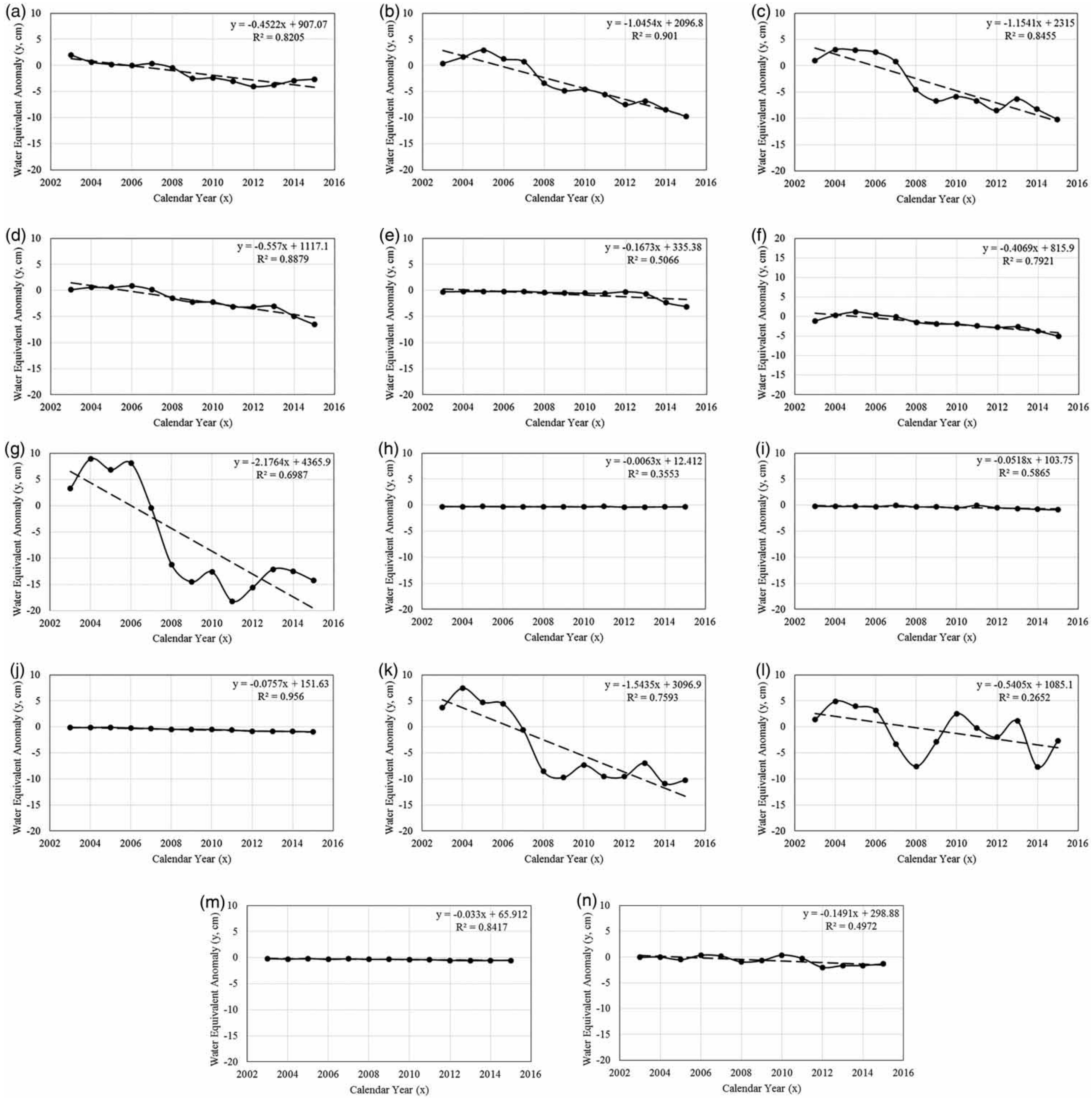

Figure 4 | Average annual WEA in 2003–2015 for: (a) EGY; (b) IRN; (c) IRQ; (d) ISR; (e) JOR; (f) KWT; (g) LBN; (h) OMN; (i) QTR; (j) SAU; (k) SYR; (l) TUR; (m) UAE; and (n) YEM.

The average WEA for the entire region was −0.513, indicating a declining trend. The computed trend components of Oman (−0.0063), the United Arab Emirates (−0.033), and Qatar (−0.0518) had the least pronounced declining trends of the WEA curves, while Lebanon (−2.176), Syria (−1.544), and Iraq (−1.154) had the most pronounced downward trends of the WEA curves in 2003–2015. The calculated trends differed among the countries; yet, all the WEA curves exhibited a descending trend. This regional declining trend of WEA is a 'supply-side' warning for water resources management in the Middle East.

The 'demand-side' of the Middle East's water resources also deserves scrutiny, because, as explained above, the regional water scarcity and water security involve resource availability and resource use. Figure 5 depicts the population changes in the Middle East from 2003 to 2015. Figure 5 reveals that the Middle Eastern countries can be categorized into two major groups. The first group including Egypt, Iran, Turkey, Iraq, Saudi Arabia, Yemen, and Syria are considerably more populous than the second group that includes Israel, United Arab Emirates, Jordan, Lebanon, Oman, Kuwait, Qatar, Bahrain, and Cyprus. On average, the combined population of the first group's countries is about 11 times larger than that of the countries in the second group. The demographic curves in Figure 5 show an average trend component of 0.419. Egypt (1.5921), Turkey (1.0453), and Iran (0.879) have relatively higher increasing population trends; while Syria (0.131), Qatar (0.146), and Israel (0.1415) have the most moderate increasing population trends. The regional rate of population growth could be problematic with respect to water scarcity and water security. The data presented herein show that both water availability and demographic indicators in the Middle East are moving in undesirable directions for resources, which can be the prelude to worsening water security in this region. The water supply vs. water use situation in the Middle East has not yet reached a 'water crisis' level. Yet, the water supply and water use trends in the Middle East ominously demonstrate that future water security in the region could be in jeopardy.

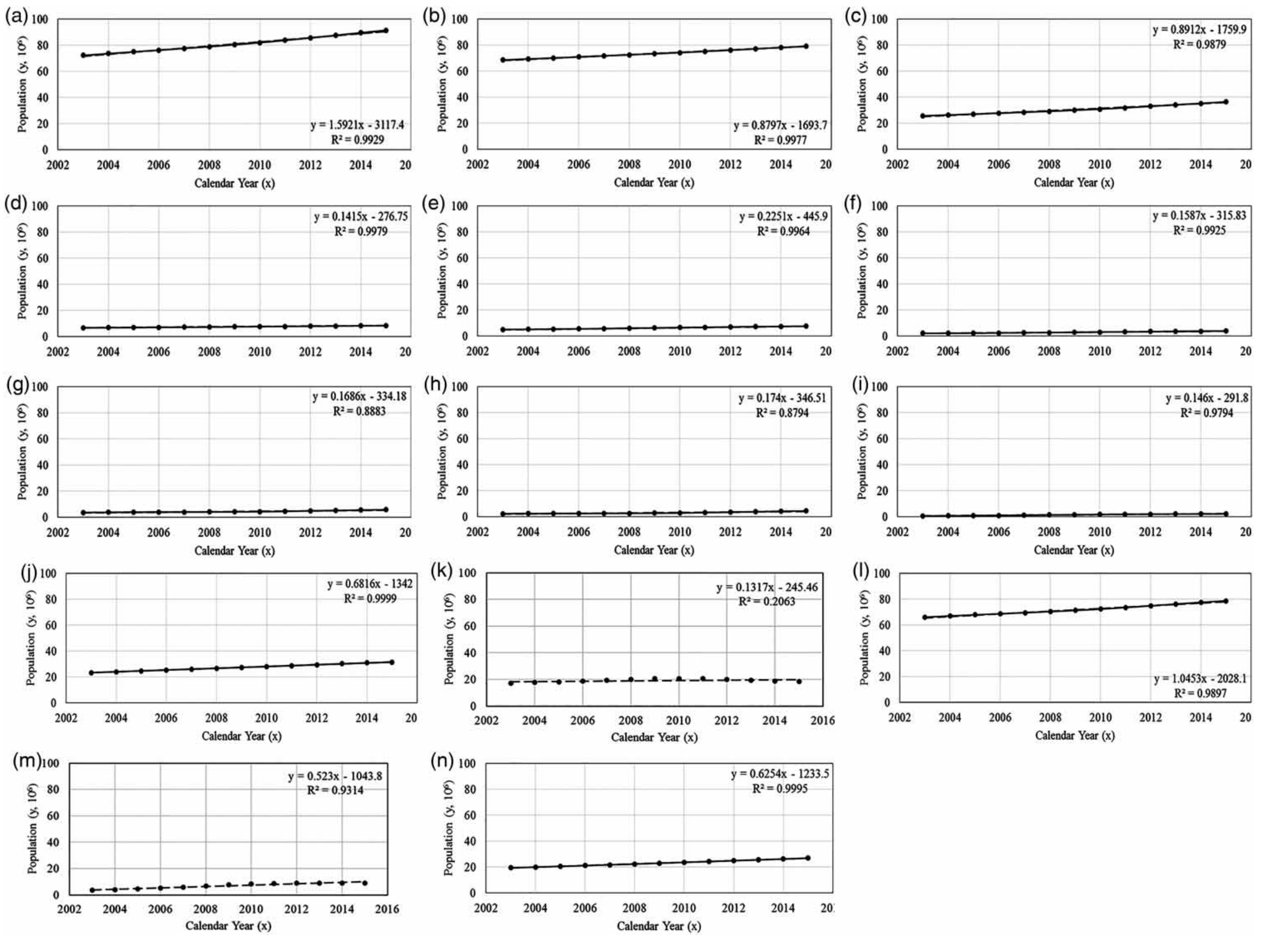

Figure 5 | Population in 2003–2015 for: (a) EGY; (b) IRN; (c) IRQ; (d) ISR; (e) JOR; (f) KWT; (g) LBN; (h) OMN; (i) QTR; (j) SAU; (k) SYR; (l) TUR; (m) UAE; and (n) YEM.

Water depletion assessment based on TWS

Figure 6 displays the average annual TWS depletion for various countries. It can be observed from Figure 6 that Lebanon, Syria, Iraq, Iran, and Israel are the top five regions with the highest TWS depletion rates in the Middle East, while Jordan, Saudi Arabia, Qatar, United Arab Emirates (UAE), and Oman have the lowest TWS depletion rates. A high TWS depletion rate implies that the region is overusing its water resources and the depletion rate is greater than the natural recovery rate of water resources. Persistence of this condition may lower the annual available water below 500 m^3 per person, which equates with absolute water scarcity for that region. Figure 6 also shows the depletion rates for the given countries in the region. While all the countries are currently under a condition of absolute water scarcity, the situation seems to be worst for Syria, Lebanon, Iraq, Jordan, Egypt, Iran, and Turkey.

Water storage status of Iran compared to its neighbors

Our analysis of the GRACE data indicates that the region-wide annual reduction in the total water storage is about 16.7×10^{-3} cm (Figure 7). Among the considered countries, Azerbaijan has the most pronounced trend of water equivalent depletion (almost 3.5×10^{-3} cm/year). This includes the depletion of surface water, soil moisture, and groundwater between 2002 and 2016. On the other hand, the water equivalent depletion in Pakistan (6×10^{-4} cm/year) is much less than that in other countries.

The percentage share of water-equivalent depletion by each country based on its fractional area in the study region is shown in Figure 8. It can be observed that water depletion in the northern and western parts of the region (including Azerbaijan, Armenia, Turkmenistan, and considerable parts of Iraq and Iran) is greater than that in other parts. This geographic pattern is suggestive of the impacts of climate changes that contribute to water scarcity due to the variations in precipitation in the study region (Evans 2008; Lelieveld et al. 2012). Turkey faces a water depletion problem that is less severe than those of its neighbors (Iraq and Iran). This may be due to its water management. Turkey operates the Greater Anatolia Project (GAP) with more than 20 dams that regulate the headwaters of the Tigris and Euphrates Rivers (Bayazit & Avci 1997). This, however, diminishes streamflow in Iraq and western Iran, which heavily affects the agricultural sectors in Iraq and Iran. Consequently, political tensions arise among these three countries. In recent years, western and southwestern Iran have faced increasingly damaging dust storms (Najafi et al. 2014), which can be considered as environmental consequences of the declining water resources in the areas. The water resources of Iraq and western Iran will be adversely impacted by the expansion and completion of Turkey's GAP. There are many transboundary or international basins, which are managed by different countries. Almost 40% of the world's population lives in such transboundary basins (Giordano & Wolf 2003), which highlights the need for comprehensive water resources management in these regions. The Middle East region, also, has several transboundary basins beset by international water management conflicts. These basins suffer from water scarcity due to climate change and population growth within a context of political instability and conflicts (Tapley et al. 2004; Seo et al. 2006).

The way forward: some potential solutions

The implication of the water security strategies in the Middle East is consistent with Hardin's principle of living within limits (Hardin 1993). Controlling the region's population growth is an obvious option to sustain life within the limits of water availability (i.e., live without exceeding the 'carrying capacity' of the water resources in the region). Reaching water and food security would be easier in a less populous region than a more densely populated region under the same other conditions. Bear in mind that there is a difference between 'controlling' and 'reduction' of population. The former is a gradual, delicate, and complex process of balancing the demand and supply. To guide the community towards the ideal population size, several socio-economic, political, cultural, and strategic factors must be taken into account.

The second option for achieving water security in the Middle East is associated with the concept of virtual water (Aldaya 2017). Virtual water refers to the water consumed in the production of goods and services. For instance, the world's average virtual water required to produce one ton

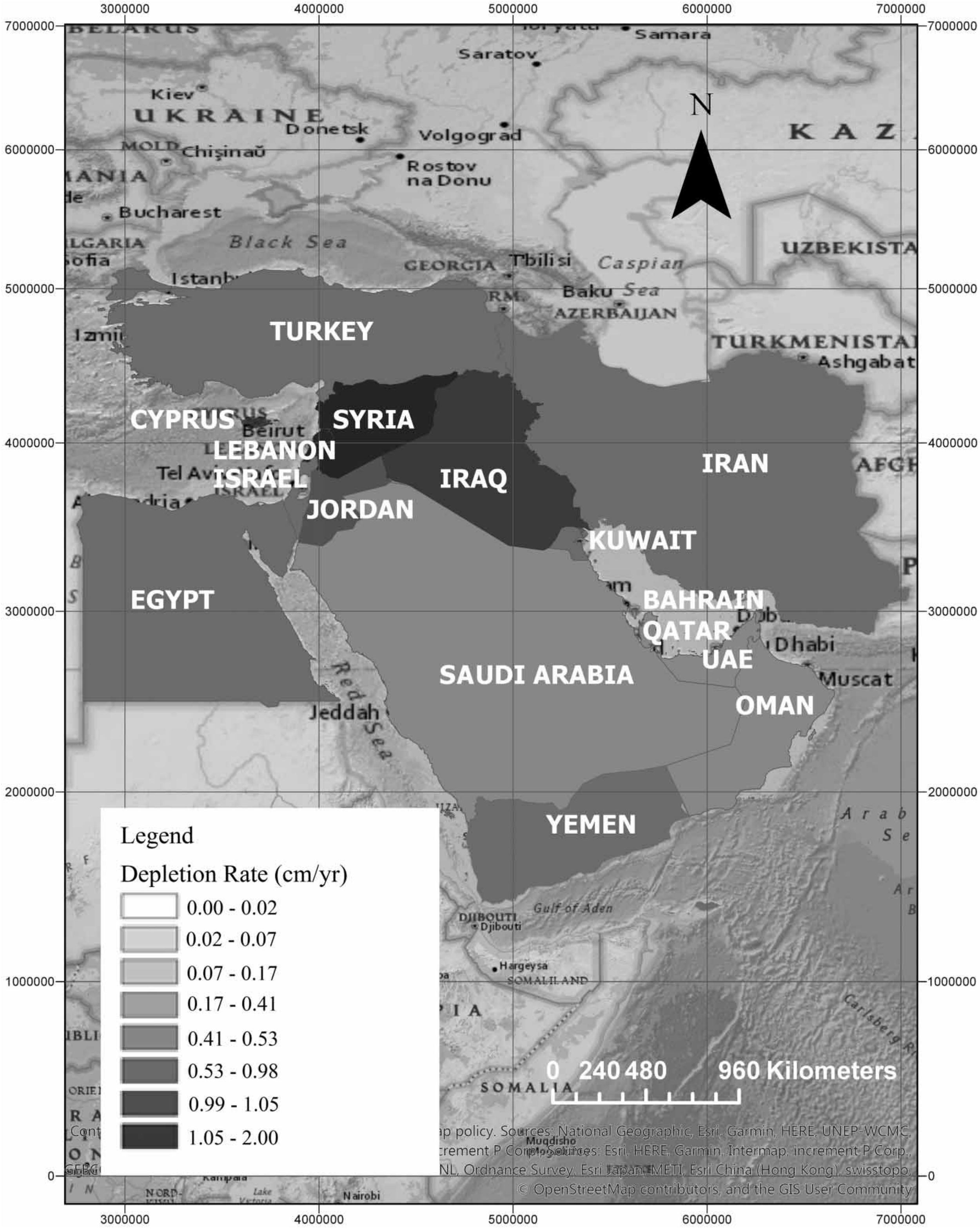

Figure 6 | Average annual total water storage (TWS) depletion (cm/year) in the Middle East countries.

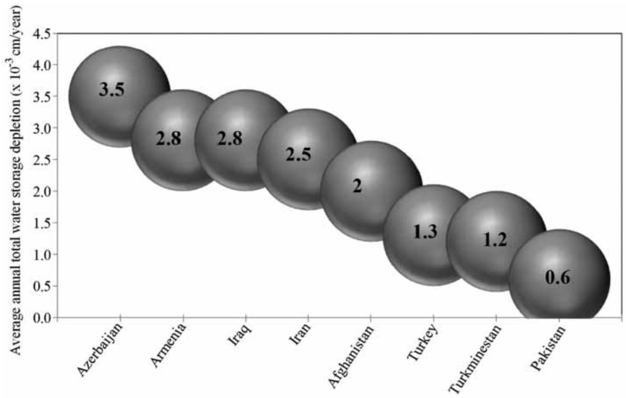

Figure 7 | Average annual water storage depletion in Iran and its neighboring countries.

of wheat equals 1,334 m^3. There is, however, variability in the virtual water to produce wheat among countries. In the Netherlands, Japan, the United States, and Russia, for example, the virtual water of wheat equals 619, 734, 849, and 2,375 m^3/ton, respectively (Craswell *et al.* 2007). Large variability of virtual water exists for other important staples such as maize. The virtual water of agricultural products is pertinent to the issue of water security in semi-arid and arid regions, because the agricultural sector consumes over two-thirds of all the water used in such regions. It is reasonable then for the Middle Eastern countries to steer their agricultural sectors to produce crops that require less virtual water and could be assimilated within their cultures and technological capacities. The crops with high virtual water requirements can be acquired through trade, if needed, recognizing the natural advantages that some countries have in producing certain foods efficiently. This constitutes strategic agricultural investment in a globalizing economy.

Virtual water trade can be a solution for mitigating water shortage in the Middle East region and it can be the first step of implementation of water resources management measures. The countries in the Middle East region may trade virtual water to reach a balance in the TWS depletion. Hence, the countries can exchange water-produced products, without transferring actual water from one place to another by construction of expensive tunnels and aqueducts. Figure 9 displays the tradable virtual water quantities (in 10^6 m^3/year) in the Middle Eastern countries necessary to achieve a water balance. It can be concluded that the TWS depletion can be eliminated in the Middle Eastern countries if virtual water trade is implemented. Further water resources improvement may follow thenceforth. The environmental and socio-economic feasibility of such trades, their potential impact in each given society, and the political and legislative mechanism to implement them would, however, require some further in-depth evaluation. While implementing these trades in a well-designed and

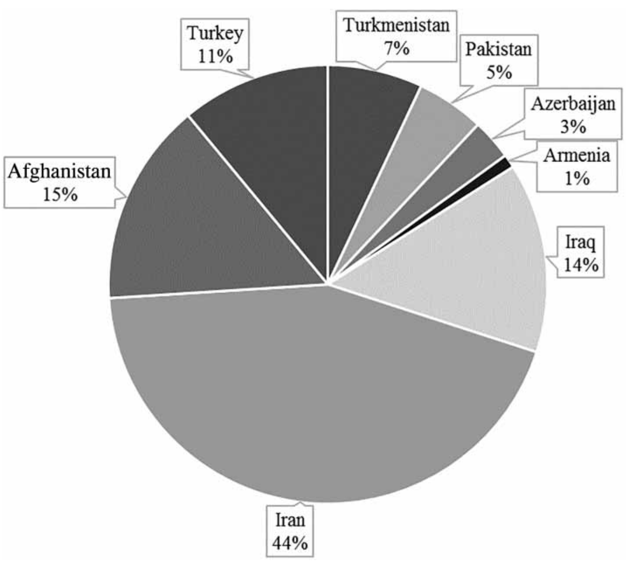

Figure 8 | Contributions of different countries to the regional total water storage depletion according to their areas.

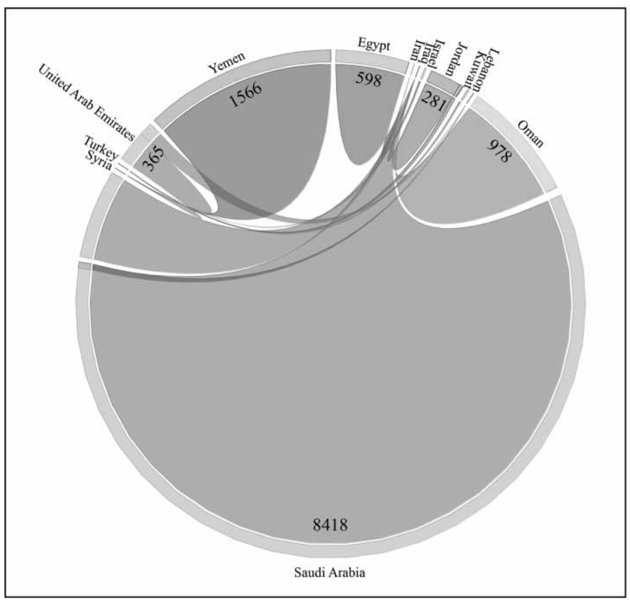

Figure 9 | Tradable virtual water necessary to eliminate the TWS depletion (in 10^6 m^3/yr).

carefully planned environment could indeed be beneficial for all involved parties, a hastily designed platform for such trades can undoubtedly do more harm than good.

Before moving on to the next potential solution, it is beneficial to elaborate on crucial points about the practice of the virtual water trade. First, one might wonder at this stage why improving the water productivity by implementing a more efficient agricultural management practice (e.g., improving the efficiency of irrigation systems or optimizing the cropping pattern) is not preferred to such trade. While there are many merits of such practices, after all, in such a semi-arid to arid region, there is only so much one can do by solely resorting to this type of solution. Not to mention that relying heavily on highly efficient methods such as high pressured irrigation systems could have adverse impacts in the long run because of the induced soil salinity problems and changes in subsurface flow and the natural cycle of recharging groundwater systems (Pfeiffer & Lin 2014). These trading practices, on the other hand, can provide a platform that could potentially permit harnessing the full potential of water, while taking all socio-economic and ecological conditions of a region into account. The crucial assumption, here, is that there must be surpluses of crops in some countries in order to make these trading practices possible. Needless to say, this is not always the case. There may be situations that while all parties are willing to be involved in such practices, they simply cannot do so, for some of them would not be able to provide the necessary goods to initiate these trades.

The third option to ameliorate the prospects of water security in the Middle East region involves seawater desalination to meet the urban water demands in coastal regions. Israel and Saudi Arabia have developed substantial capacities in this respect. Israel relies heavily on solar energy (abundant and reliable in the Middle East) to power desalination plants. In addition, recycling of municipal sewage to produce additional potable urban water through either direct or indirect water reuse is another alternative solution that has been increasingly adopted in water-scarce regions. However, one should note that both desalination and recycling are relatively expensive options when implemented at large scales. Based on the current technology, the economic feasibility of these methods may be questionable, since their infrastructure, operation, maintenance, and energy cost would dramatically escalate at such operation scales. In addition, the disposal of the by-products of both methods in large-scale operations poses an environmental challenge (Angelakis *et al.* 2003; Ghaffour *et al.* 2013).

CONCLUSION

This study has shown water scarcity is a worsening condition in the Middle East. Precipitation and temperature regimes, climate change, population growth, and short-sighted management of water resources are the main causes of water depletion and the induced environmental problems such as dust storms, displacement of populations, and the tension over water conflicts. This paper presented a survey of the water equivalent anomaly and population growth in the Middle Eastern countries. The results indicated that the region's water resources were declining, while the water demands were increasing. Additionally, the data and analyses demonstrated the imminent threat to the sustainability of the water resources in the region. In particular, Lebanon, Syria, Iraq, and Iran might have reached critical conditions in terms of their water resources.

Corrective measures were, also, discussed to achieve future water security. The suggested precautionary and corrective options include: (1) controlling population growth; (2) strategic investments in the agricultural sector and virtual water trading; and (3) applications of seawater desalination and water reuse technologies powered with renewable energy. The first measure solely tackles the water crisis from the demand point of view, while the third option just aims at the supply side of water resources; the second option takes into account both demand and supply sides of water resources management. In addition to these potential corrective measures, it is crucial to bear in mind that any meaningful and long-lasting changes in the water resource management of the region require the collaboration of all the Middle East countries. Reaching agreements among these countries to share the trans-boundary water resources, however, is challenging and time-consuming. Yet, such agreements are necessary to preserve the regional water resources and to achieve the harmonious coexistence of the involved countries. Taking advantage of the shared cultural and religious traditions may pave the way for reaching such agreements.

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