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Managing the water-energy-food nexus on an integrated geographical scale

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ABSTRACT

The water-energy-food (WEF) nexus is the subject of much research focusing on different aspects, a wide range of issues, and development of a variety of models and tools. This study takes a different approach by developing a holistic framework that concentrates on the spatial elements of continuity and change associated with WEF transition on national, regional, and international scale. The study also investigates the interconnected challenges that could affect these resources and the actions and polices that should be taken on different geographical scales to address these challenges. The results can help practitioners and policy makers gain a clearer understanding of the state of the knowledge when performing WEF nexus assessments at different geographical scales.

1. Introduction

The water-energy-food (WEF) nexus has drawn great attention and prompted significant research because of growing concern about scarcity of these resources and their interdependencies. WEF nexus analysis can assist policy and decision makers in WEF conservation and sustainability (Kurian, 2017; Dai et al., 2018; Abulibdeh et al., 2019a). WEF resources are increasingly interlinked on many geographical scales by resource constraints, environmental constraints, technology, markets and speculation, demand and supply, trade, and trends in agricultural commodity and energy prices (Ringler et al., 2013).

The main aim of the WEF nexus is to transmit normative implications that consider the processes of producing, distributing, and consuming WEF resources into a decision-making process and to manage them more effectively and efficiently (Hussien et al., 2017; Endoa et al., 2017; Abulibdeh, 2019). The significance of the WEF nexus is manifest, because of the increased stress and shortages of these resources, accompanied by rapid population growth and economic prosperity, changing consumption patterns, climate change, and competing land-use patterns. Therefore, it is considered a major component in national sustainable development strategies and simultaneously as an indicator of the level at which WEF security objectives are achieved (Golam and Sharma, 2015; Biggs et al., 2015; Endoa et al., 2017). The nexus augments understanding of the interconnectedness, resource conflict, and trade-offs accompanying operation of the WEF processes of producing, distributing, and consuming these resources. These sectors are linked and integrated through several sub-nexus levels (i.e., water-energy nexus), and in multidirectional and complex ways (Rasul, 2014; Weitz et al., 2014; Rasul and Sharma, 2015). Ratifying the interdependences and trade-offs between these resources can result in advance synchronization of the interactive effects among WEF sectors, as they are inextricably linked. Each of these sectors reinforces and imposes constraints on the other and is affected by actions taken in any of the other sectors, so achieving security in one sector

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depends on development in other sectors (Hoff, 2011; (Mohtar and Lawford, 2016; Hussien et al., 2017).

WEF security interacts and is integrated with economic sustainability and is significant for sustainable development due to rapid population growth and growth in economic activities (Rasul, 2016; Kurian, 2017). This intertwining is significantly stronger under growing scarcity of these natural resources. The prices of these resources are very susceptible to various factors at different geographical scales, and hence any significant increase in price will have significant implications for the geographical distribution of economic activity and development (de Amorima et al., 2018). At the national level, WEF security policies aim to invest in reducing demand for overseas imports, while at the same time protecting overseas supplies, which depends mainly on the geographical scale at which WEF resources should be governed (de Amorima et al., 2018). The rapid national, regional, and international population and economic growth, globalization, urbanization, climate change, and aging infrastructure add more pressure to these resources (Bonn Nexus Conference, 2011; World Economic Forum, 2011). The geographical implications of the WEF nexus are not well defined; therefore, there is a need to investigate the WEF nexus and its integration and interaction, as well as the main challenges and the most appropriate responses/policies to overcoming these challenges at different geographical scales. Identifying these geographical implications will give more insights into the factors affecting WEF nexus. Since WEF resources are interdependent, decision makers should cooperate to resolve related issues in national, regional, and international resource management. Good spatial interconnectedness can provide a holistic view of WEF resources at different geographical scales.

The overall aim of this study was to develop a holistic and comprehensive systemic framework to optimize WEF resources management and to capture the integration and interactions between these resources, in order to contribute to economic development at the national, regional, and international levels. A further aim was to investigate the interconnected challenges that could affect these resources, and the actions and polices that should be taken on different geographical scales to address these challenges. The interlinks between national, regional, and international economies, sector policies, and cross-sector impacts are not internalized into national policies. The intention with the framework developed in this study was to investigate geographical integration of WEF sectors through the nexus and the integration of policy options for minimizing trade-offs and maximizing synergies regarding these resources. Another intention was to develop a holistic approach for better coordination of these resources at different geographical scales.

The study focused on the Gulf region, an arid and semi-arid region characterized by water and food scarcity, but rich in energy resources. The WEF nexus in this region can be explored at multi-geographical scales. Therefore, the work focused on framing WEF based on integrated geographical scales (i.e., national, regional, and international levels). National-level research on the WEF nexus mainly focuses on assessing these resources in terms of availability, interdependences, accessibility, and flows in a specific country, based on its household, rural, and urban levels. Regional-level research on the WEF nexus focuses on integration and interconnectedness between these resources based on an economic bloc, the Gulf region in the present case. International-level research aims to assess the WEF nexus at the larger geographical scale. This includes analysis of the integration, availability, and accessibility of WEF resources from small scales (i.e., household) to regional and international scales. In the present study, we considered the development of cross-sector policies that may result in more resilient and adaptable communities, in attaining the United Nations (UN) Sustainable Development Goals (SDGs), and in greater economic diversification. The study adds to the literature by improving overall understanding of the relevance of the WEF nexus at different geographical scales. The holistic WEF nexus framework presented here can benefit policy and decision making for economic sustainability, as it can help build synergies, increase benefits for humans, and reduce trade-offs across sectors at different geographical scales.

2. Purpose of the study

Since their establishment, the Gulf Cooperation Council (GCC) countries have been characterized by dynamic and significant socio-economic development, and extensive efforts to diversify their economies (Abulibdeh et al., 2019b; Abulibdeh and Zaidan, 2017). As a result, these countries are among the fastest growing in the world, with fast urbanization, rapid economic growth, and strong increases in population, which is projected to reach 77 million by 2050 if the current growth rate is maintained as shown in Fig. 1 (ESCWA, 2017). These countries have also witnessed increasing demand for WEF resources, with critical implications for long-term WEF security. One of the challenges facing them is to ensure WEF security without exhausting the natural resource base, particularly the fossil fuels resource, to achieve sustainable development (Siddiqi and Anadon, 2011).

The WEF nexus in arid regions is gaining increasing interest from policy makers and environmental organizations because of prolonged drought. This drought is considered a significant catalyst in emphasizing the linkages of WEF resources, and is associated with depending on desalinized water using conventional fossil fuels. In this context, the Gulf Region is classified as an arid region with water and food scarcity, but rich in natural conventional fossil fuels (Abulibdeh et al., 2019a).

Table 1 shows the WEF index for the GCC countries (Efron et al., 2018). This index is built-up on developing a single score for overall water, energy, and food resource vulnerability by combining country scores for these resources. Each of these single scores consists of a composite measure of sub-factors for availability and accessibility of these resources (RAND, 2018). The value of the index ranges from 0.0 (lowest security) to 1.0 (highest security). For the GCC countries, the values are close to the middle of the full range (0.39 for Kuwait to 0.54 for Oman). These scores result from a low-water sub-index, a high-energy sub-index, and a mid-level food index. The water sub-index is driven by adaptive capacity, which capture total per-capita internally available renewable water. Geographical drivers of water scarcity have been aggravated by elevating per-capita water consumption, in addition to economic prosperity and population growth. The scores of the energy sub-index for all the GCC countries are high because of the abundant amount of oil and gas resources and hence provide easy access to electricity and modern fuels as well as a large electricity consumption. The food sub-index shows that the GCC countries have high scores for food availability and medium scores for food

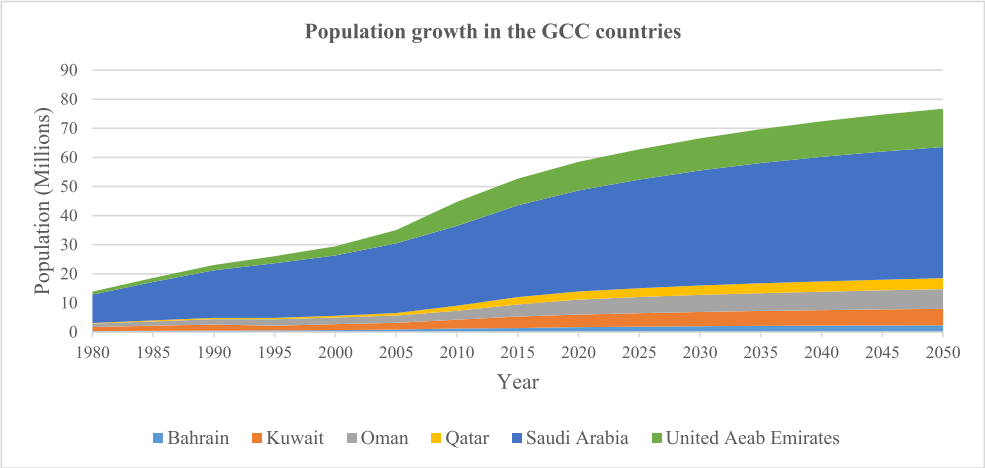

Fig. 1. *Population growth in the GCC countries. Source (ESCWA, 2017).*

Table 1
GCC WEF index scores as of 2018. Source (Efron et al., 2018).

Country	WEF Score	Water Sub-index	Water Accessibility	Water Availability	Water Adaptive Capability	Energy sub-index	Energy Accessibility	Energy Availability	Food Sub-index	Food accessibility	Food Availability
Bahrain		0.26	1.00	1.00	0.02	0.90	0.96	0.84		0.45	
Kuwait	0.39	0.10	0.99	1.00	0.00	0.92	0.96	0.88	0.64	0.47	0.87
Oman	0.54	0.30	0.95	0.41	0.07	0.88	0.96	0.80	0.60	0.43	0.83
Qatar		0.17	0.99	1.00	0.01	0.92	0.96	0.89		0.57	
Saudi Arabia	0.51	0.25	0.98	0.93	0.02	0.89	0.96	0.83	0.61	0.42	0.87
UAE	0.45	0.14	0.99	0.92	0.00	0.91	0.96	0.85	0.70	0.58	0.85
GCC Average	0.47	0.20	0.98	0.88	0.02	0.90	0.96	0.85	0.64	0.49	0.86

Sources: RAND, 2018; Note: Overall indices are not available for Qatar and Bahrain given that a food availability index for these countries was not determined given data limitations.

accessibility.

In the GCC countries, production of water and electricity is inextricably linked. Power plants in these countries usually produce a combination of desalinated water and power. The input fuels of these plants rely almost exclusively on fossil fuels. Table 2 shows electricity and water production and consumption in these countries. The entries of the table shows that these countries produce and consume electricity generated within national levels. In 2015, Saudi Arabia was the largest producer of electricity in the region as the country produced 304 TWH and delivered 274.5 TWH to customers. In terms of water production and consumption, all water production in these countries originated from desalinization. The GCC countries are self-sufficient and consume almost the same amount they produce except Saudi Arabia as they produce 30% more than they consume as shown in the table.

Table 3 shows the domestic production, exports, and imports for crude oil and natural gas. The table shows that Saudi Arabia is the largest crude oil producer and exporter followed by the UAE, while, on the other hand, Qatar is the largest producer of natural gas. The percentage of imports of these resources in some of these countries is very low, where Bahrain is the largest importer of crude oil in the region and all its imports comes from Saudi Arabia.

Given the abundance of fossil fuel resources in the GCC countries, the power and water system rely exclusively on these resources. Table 4 shows that natural gas is the primary fuel consumed at about 2.8 quadrillion British thermal units (QBtu), while crude oil,

Table 2
The electricity and desalinated water production and consumption in the GCC countries as of 2015. Source (Wogan et al., 2017).

Country	Electricity (terawatt-hours (TWh))		Water (million m3)	
	Production	Consumption	Production	Consumption
Bahrain	14.1	12.6	174.9	174.4
Kuwait	68.3	60.5	562.1	533.2
Oman	31.3	31.3	228.6	222
Qatar	38.7	36.1	495.0	495.0
Saudi Arabia	304.2	274.5	2269.6	1600
UAE	116.6	111.7	1756.4	1693.3

Table 3
Domestic production, exports, and imports for crude oil and natural gas as of 2016. Source (Wogan et al., 2017).

Country	Crude oil			Natural gas		
	Production (million bbls)	Export (million bbls)	Import (million bbls)	Production (QBtu)	Export (QBtu)	Import (QBtu)
Bahrain	73.6	54.8	78.7	0.76	0	–
Kuwait	1050	720	0	0.64	0	0.137
Oman	358	287	0	1.13	0.38	0.07
Qatar	230	170	0	6.4	4.6	0
Saudi Arabia	3700	2600	0	2.9	0	0
UAE	1070	890	0	2.8	0.47	0.36
Total GCC	6481.6	4721.8	78.7	14.63	5.45	0.567

Table 4
Estimated fuel consumption and regulated prices by power and water sectors as of 2016. Source (Wogan et al., 2017).

Country	Crude oil		Natural gas		Diesel		Heavy Fuel Oil (HFO)		Total
	Consumption (TBtu)	Price (USD/bbl)	Consumption (TBtu)	Price (USD/MMBtu)	Consumption (TBtu)	Price (USD/ton)	Consumption (TBtu)	Price (USD/ton)	Consumption (TBtu)
Bahrain	–		235.3	2.75	–	268.48	–	–	235.3
Kuwait	26.3	13.77	354.6	3.53	46.9	496.6	274.3	98.90	702.1
Oman	–	–	264.2	3	–	–	–	–	264.2
Qatar	–	–	433.6	1.00 to 2.00	–	–	–	–	433.6
Saudi Arabia	865.1	6.35	670.3	1.25	469.8	105.26	275.0	28.52	2280.1
UAE	1.0	–	1219	1.00 to 2.00	0.7	–	18.1	–	80.7
Total	891.4		3177.0		518.5		567.4		5154.3

heavy fuel oil (HFO), and diesel cover almost 1.9 QBtu per annum as of 2015. A significant amount of crude oil, diesel, and heavy fuel oil are used in Saudi Arabia to produce power and water. Natural gas is used extensively to produce water and electricity in Oman, Qatar, UAE, and Bahrain. Assessing the actual production costs of water and power is difficult for each country as the prices are not always published or are not transparent. Table 4 shows the regulated prices of selected fuels for the water and power sectors as of November 2016. These subsidized prices is a significant factor of the economic barriers to increasing coordination among GCC energy systems and make these countries wary of exporting them.

The countries in this region pay little attention to understanding and managing the interdependencies of WEF sectors. In addition, policies related to these sectors are taken in isolation and are sector-based, disconnecting resource management. These policies lack adequate consideration of cross-sector consequences and neglect the impact of these sectors on each other. Consequently, these policies result in a discrepancy between the sectors in terms of supply, and demand and shift the crisis from one sector to another, leading to severe resource constraints (Scott et al., 2011; Hermann et al., 2012). Conversely, proper management and understanding of the linkages between these resources can minimize conflicts between the sectors and promote synergies and resilience in policies and instruments (Newell et al., 2011; Sharma and Bazaz, 2012).

The GCC countries are currently stimulating development through economic diversification. The core of this diversification is manufacturing (i.e., production of fertilizer, steel, aluminum, hydrocarbons), services (tourism, real estate), agriculture (i.e., animal production and dairy products), and significant events (i.e., the Expo Dubai, 2020 and the 2022 FIFA World Cup in Qatar) (Zaidan and Abulibdeh, 2018; Callen et al., 2014). However, these sectors and developments depend on water and energy production and utilization, and demand more agricultural commodities. At the same time, these countries are facing challenges in producing water and food due to increasing stress on these resources, and depend mainly on fossil fuels to provide energy for the emerging sectors. This stress is amplified by population growth, economic prosperity, changing lifestyles, and urbanization. Therefore, the WEF nexus is significant to these countries in achieving balanced solutions to economic, resource, and environmental problems (Keulertza and Woertzb, 2015). Furthermore, the nexus provides more holistic information on relative resource scarcity and productivity, and on the potential for sustainable intensification at different geographical scales. Analysis of the interdependences between WEF resources in these countries can lead to identification of more resource-intensive production schemes to be allocated in these countries, which requires regional and international collaboration.

3. The geographical framework of the WEF nexus

The spatial organization of national, regional, and international economies is affected by the policies employed to attain WEF self-sufficiency and a low-carbon energy transition. The geographical distribution of economic activity depends on the historical relationship between WEF, economic production, and the environment (King and Carbajales-Dale, 2016; de Amorima et al., 2018).

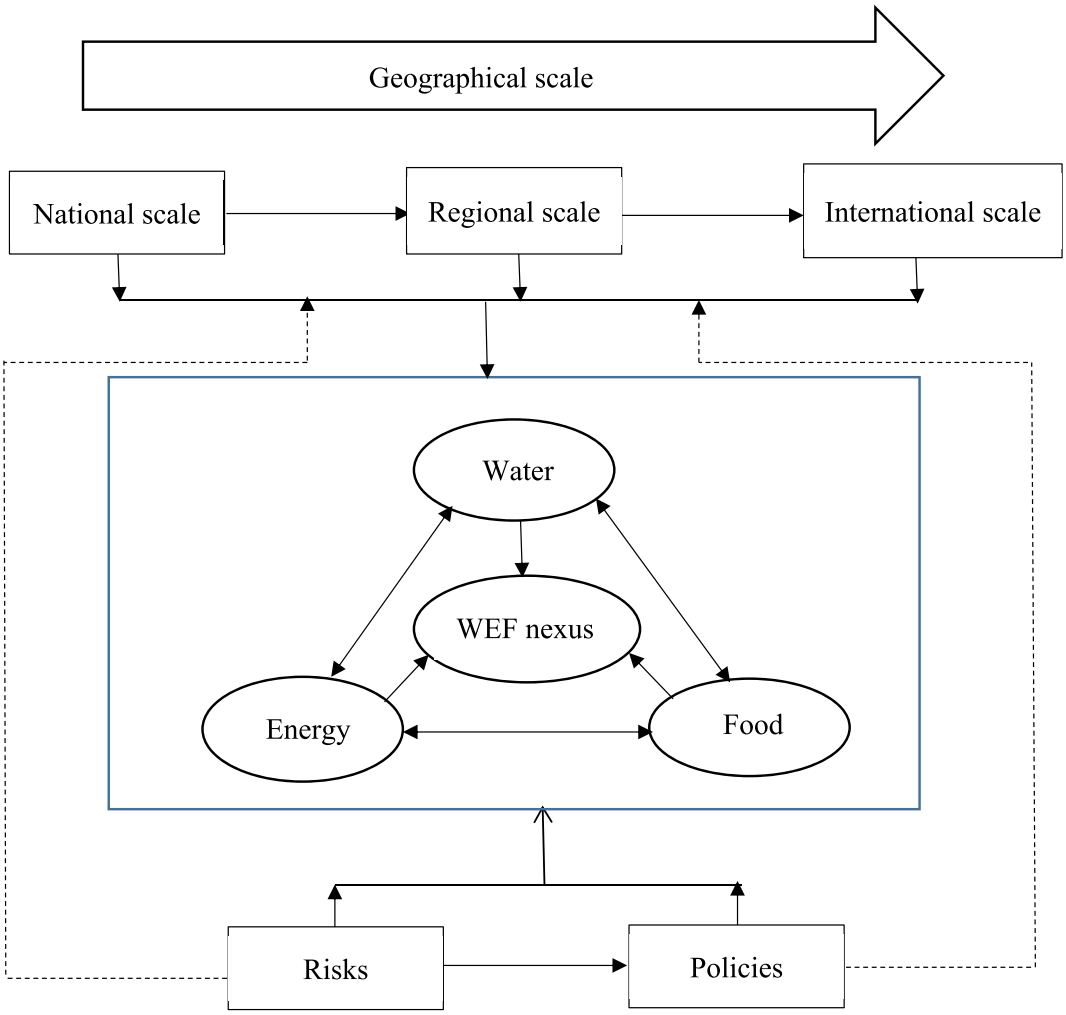

Fig. 2. Conceptual framework illustrating the geographical scale of the water-energy-food (WEF) nexus.

Therefore, the linkages and interactions between these resources require assessment of the challenges, risks, and unexpected consequences faced by the global society.

Framing the geographical interconnectedness of WEF sectors is crucial for understanding the coherence and strength of coordination between these sectors. It helps decision makers develop a holistic view of the linkages between WEF sectors and shifts the decision-making process towards developing institutional mechanisms to synchronize the decisions of different authorities and to strengthen synergies and complementarities among the three resources at various geographical scales.

Fig. 2 shows the structure of our holistic geographical framework for WEF resources. A bottom-up approach was used to develop the framework, encompassing the linkage between WEF resources at different geographical scales. The framework captures the national, regional, and international level dimensions of the WEF nexus and has different dimensions that can assist appropriate policy formation and analyze the interdependencies of these resources at different geographical scales. It involves two steps:

1) Specifying the interconnectedness and integration between these resources on national, regional, and international geographical scales. This can help find a suitable strategy to achieve sustainable and efficient management of these resources.
2) Evaluating the risks threatening the interconnectedness of these resources at different geographical scales. This can help in planning for new strategies to overcome these risks.

The aim of the framework is to help to understand geographical integration of these resources and the potential contribution of their sustainable management from the local to the international scale. The framework can thereby aid the emergence of best practices and prioritize schemes for resource-efficient usage. The framework is suggested for cross-sector management and coordination. It can provide more holistic information on relative resource scarcity and productivity, and the potential for sustainable intensification at different geographical scales. It illustrates a holistic geographical transition of the interdependencies and trade-offs between WEF resources. In addition, it illustrates a geographical dimension of the WEF nexus where the focus is on the spatial

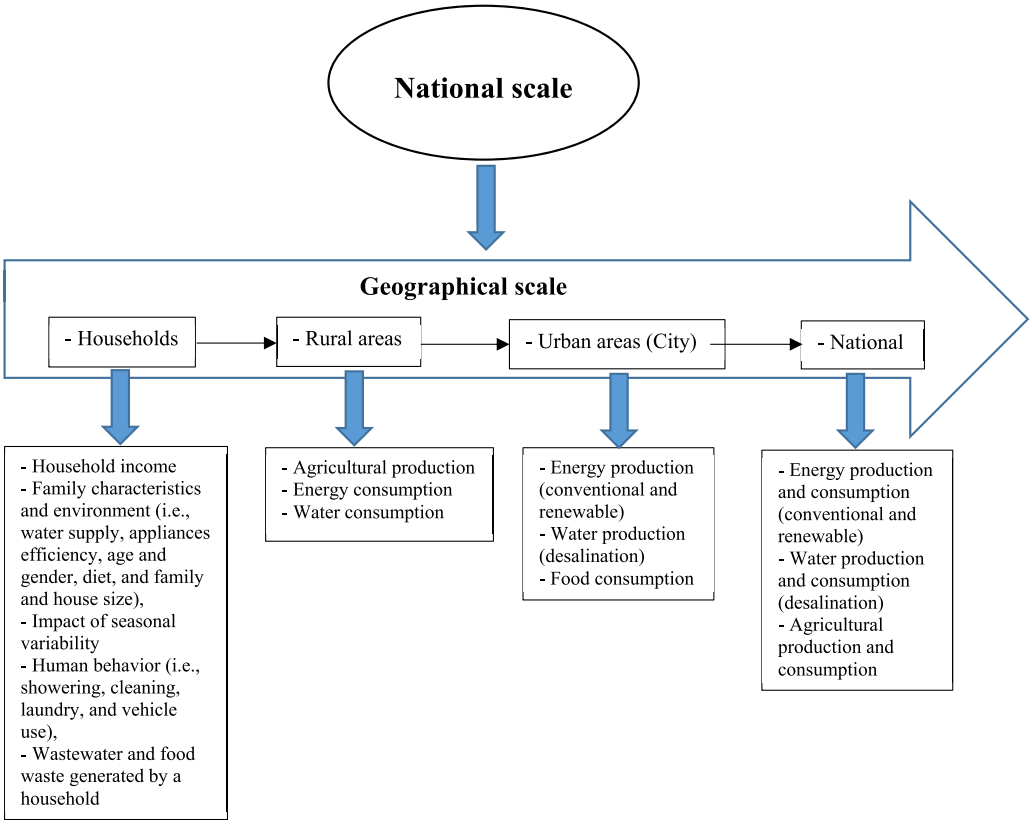

Fig. 3. Geographical framework of the water-energy-food (WEF) nexus at the national scale.

processes that shape the three resources and the challenges to their capacity for transformation. The following sections discuss each of the framework components in detail.

4. National scale

At the national scale, the key variables of the WEF nexus are at the household, rural area, urban area (city), and national levels, as shown in the national-scale framework (Fig. 3). The framework addresses the interaction between WEF sectors starting from the end-use level at the household scale, then moving up to investigate the nexus at other geographical sub-scales within the national scale.

Households consume a significant proportion of the WEF resources in cities to meet their demand. Therefore, the household is the most appropriate unit of demand for influencing consumption practices. WEF consumption at the household scale can be disaggregated into different variables that could affect household consumption of these resources (Daioglou et al., 2012; Hussien et al., 2017). These variables include household income, family characteristics and environment (i.e., water supply, appliance efficiency, age and gender, diet, and family and house size), impact of seasonal variability, human behavior (i.e., showering, cleaning, laundry, and vehicle use), and wastewater and food waste generation by households (Grafton et al., 2011; Hussien et al., 2017). However, household income is a significant driver impacting per capita WEF consumption, because it reflects the increased probability of affordability and accessibility when income increases (Palmer et al., 2013; Willis et al., 2013).

The key issue at the household scale is end-use parameters related to consumption of the three resources. At the end-user level, energy consumption may depend on type of energy uses, appliance usage, and inflow and outflow water temperature, while water consumption may include flow rate and frequency of water usage. Food consumption may include consumption of each food commodity (i.e., cereal grains, vegetables and fruits, meat, sugar, dairy products, and oils and fats) (Isaacs et al., 2004; Aguilar et al., 2005). Another crucial factor in household consumption of these resources is the interaction between e.g., energy and water for food preparation, energy consumption for water heating, energy for food preservation, and water for space cooling (Hussien et al., 2017).

Food waste is a significant element in the WEF nexus at household level. Food waste depends on per capita food consumption (Grafton et al., 2011; Hussien et al., 2017). The percentage of food waste should be estimated at the household level as part of the process of producing, processing, distributing, and consuming food (Kenway et al., 2013).

In the GCC countries, there is a positive correlation between income and economic growth, and WEF consumption (Sadorsky, 2011; Bhutto et al., 2014). In these countries, people are concentrated in urban areas due to economic prosperity and internal migration, and the inflow of expatriate workers (Abulibdeh, 2018). This is accompanied by increasing size of the average dwelling,

increasing use of household appliances, and a greater reliance on ambient air conditioning. Relatively low cost of these resources to the end-consumer is another factor increasing their rate of consumption. Prices are subsidized in the GCC countries, so the end-user does not pay the full cost of consumption (Hertog and Luciani, 2009; Kinninmont, 2010).

Our framework moves from the household scale to the rural scale (Fig. 3). The GCC countries are characterized by their aridity, where fresh water and food production are scarce and a concern. At the rural level, agricultural commodities in some GCC countries (such as the Sultanate of Oman and Saudi Arabia) meet a small proportion of the country's food demand. However, this is associated with high water use and consumes crucial economic resources (Al-Kandari and Jukes, 2009) Consequently, achieving sustainable food self-sufficiency is unattainable due to high temperature, low rainfall, and soil conditions.

At the city scale, many cities in the GCC countries are primary hubs regionally and globally, and attract people from rural areas. Urbanization is increasing in all GCC countries, and in 2015 ranged from 77% in the Sultanate of Oman to 94% in the State of Qatar (ESCWA, 2017). The city is the core system for WEF and therefore supply and demand of WEF resources are intensive and complicated. At the city scale, residential, commercial, and industrial sectors are significant in WEF consumption. This must be considered in prediction of supply and demand of WEF resources at the national scale. In addition, sustainable and effective management of linked WEF sectors is significant for sustainable development at the city scale.

Providing water and food to different land uses in the city is one of the challenges that each country in this region faces if it is to achieve sustainable development under constraint of these resources. The GCC countries depend mainly on importing food and desalinizing water to meet their needs for these two resources, using the revenues gained from exporting energy products. However, subsidizing WEF resources can be counterproductive because it encourages the overexploitation of these resources by end-users and negatively affects the environment. This process is not sustainable and puts these countries under WEF security risks.

Developing renewable energy is a significant factor in achieving future sustainable development and WEF security in the GCC countries. Increasing the share of renewable energy in their energy grids would allow them to export more oil and gas as domestic use decreases. However, there are varying attitudes to adoption of renewable energy between these countries. Some have started diversifying their energy resources by investing in renewable energy technology-intensive sectors, while other countries are lagging behind and still prefer to use conventional energy sources (mainly oil and gas). There are many renewable energy options available in these countries (i.e., solar, nuclear, tidal, and wind energy).

Utilizing renewable energy can also benefit the water sector, because water use is linked to energy supply. Energy is a significant component in water extraction, desalination, and distribution to the end user. Therefore, water security and water supply can be enhanced by utilizing renewable energy (Bhutto et al., 2014). Moreover, the energy efficiency of water utilities and the resilience of the supply network can be improved by using renewable energy solutions. Energy costs comprise a high proportion of the costs in the operating budget of water utilities, and therefore the operational risks may increase when relying on a volatile or expensive energy source (Atalay et al., 2016). All countries in the GCC region depend mainly on desalinized water to meet their demand. Therefore, using renewable energy-based desalination technology could replace the intensive use of conventional energy resources in the desalination process, which is currently not sustainable from an economic or environmental perspective. Using renewable energy to supply the heat or electricity needs of desalination plants would provide the opportunity to decouple water production from conventional energy sources. These technologies are less water-intensive across their life cycle. For example, solar photovoltaic (PV) and wind energy require minimal water compared with conventional thermoelectricity generation.

In terms of WEF security, renewable energy technologies can achieve some of the trade-offs between these resources by providing energy services using less resource-intensive process and technologies. Renewable energy can enhance security of supply across the WEF sectors and at the same time offer integrated solutions for expanding access to sustainable energy. Energy transition in the GCC countries can capture changes in the spatial organization of WEF sectors and economic activity at different geographies at the national scale. Hence, the WEF nexus in these countries should acknowledge the spatial dimensions of WEF transition.

Food security is significant to the GCC countries due to rapid population growth, economic prosperity, and intensive urbanization. Although these countries are located in an arid region, they are classified as food secure. Self-sufficiency in agricultural products is not a precondition to achieving food security at the national level. Generally, national per capita food production is considered an indicator of the level of food security, so food security can be achieved if a country generates enough revenue from its exports to finance food imports. Consequently, the ratio of a country's total exports to food imports could be used to indicate whether it is food secure at the national scale (Yu et al., 2009). This concept indicates the relative cost of access to food, the capacity of a country to export, and the demand for imports in each country. When applied to the GCC countries, it reveals that food security is not equal to food self-sufficiency. The main reason is that these countries are rich and thus the ratio of total exports to food imports is high. Thus, while these countries are achieving a high level of food security at the national level, their food security is vulnerable to food prices, oil and gas prices, and supply risks.

5. Regional scale

Integration and collaboration between the countries in a region is significant in addressing some of the important challenging aspects of the WEF nexus. The countries in the Gulf region have similar characteristics regarding the WEF resources, i.e., they are rich in conventional energy resources but scarce in water and food resources, and have water and food security challenges at the national level. Furthermore, these countries have similar climate and soil conditions. Considering population and economic growth, WEF security and meeting the growing demand for these resources are among the challenges that face the region when seeking to achieve sustainable development, particularly under constraints on water and food resources. WEF security concerns also derive from the direct uncontrollable utilization of these resources that these countries face, which is leading to increasing demand. Economic and

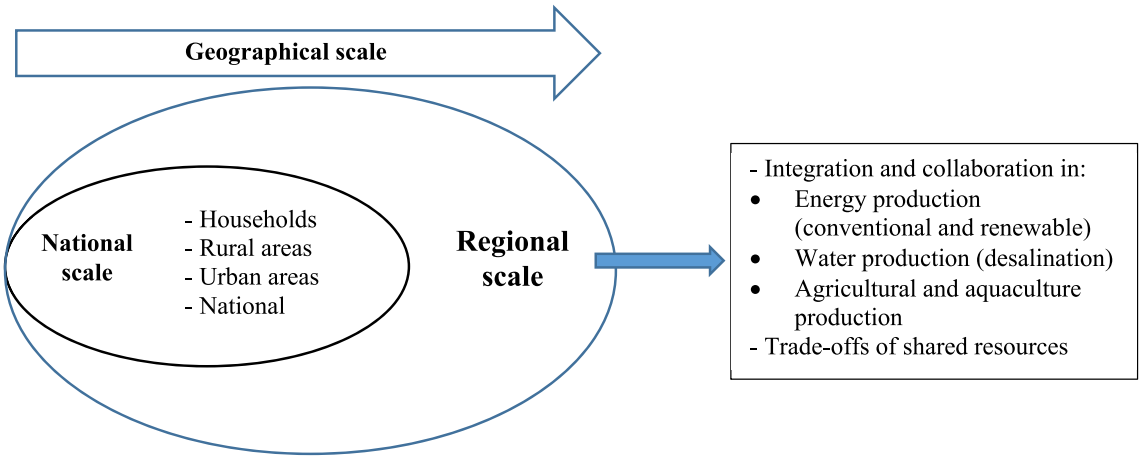

Fig. 4. Geographical framework of the water-energy-food (WEF) nexus at the regional-scale.

population growth has resulted in massive urbanization in the region, which puts more pressure on the WEF demand. Furthermore, urbanization in the region has changed both the pattern and the intensity of WEF consumption, which in turn has brought more pressure to bear on ecological conservation and resource allocation. Therefore, an integrated and collaborated effort to find effective measures to harmonize the utilization of WEF resources at regional level is essential to support the continuing process of urbanization and economic diversification as shown in Fig. 4.

Depending on conventional sources of fuel for desalinizing water and financing food purchase jeopardizes the long-term sustainability of WEF resources in the region, and poses challenges to achieving the SDGs. On the other hand, governments in the region often work in an isolated and fragmented way despite the essential interconnections between these resources. In this arid region, WEF security requires collaboration and integration on a larger geographical scale than the national scale. Integration and collaboration between the countries in this region can be considered a critical first step in achieving water affordability, access, and safety for all countries, as well as energy security, through continuity of energy supply relative to demand at a given price and food security based on food availability, accessibility, and stability over time.

The national rate of WEF consumption is significantly correlated to economic development, which shows the importance of the distribution of different WEF-related activities at the national scale and the integration between this scale and the other geographical scales in the contemporary patterns of economic activities. In terms of supply dependence, the WEF nexus is framed as a geopolitical issue. For example, the GCC countries depend on food supplied by other countries within the same region and throughout the world. Water security in the region can be a geopolitical security threat. Therefore, joint water agreements between the countries regionally can foster broader collaboration in easing water stress, particularly that caused by utilizing water for conventional thermoelectricity production.

Water security is well-known characteristic in this region. As mentioned, the GCC countries depend on desalinized water to meet their demand, which requires significant energy use. Desalination is considered a strategic choice in the region, and most of the desalination plants in the world are located in this region. Currently, natural gas is the main source of the electrical energy needed to desalinize water in the region. This results in high water production costs and means that the affordability of water supplies can be altered by volatile energy prices. Using natural gas or oil to desalinize water also has harmful implications for the environment. Therefore, using new desalination innovations, new technologies, and renewable energy resources for desalination can reduce the cost of energy inputs and ultimately reduce the cost of water production. At the same time, it could be an important solution to the environmental and oil-related challenges and risks facing the desalination process. Renewable energy can ensure the long-term reliability of water supply and can provide access to sustainable, cost-effective, and secure energy along various stages of the water production chain.

Conventional energy resources are the main element on which the GCC countries depend for developing their economies. Furthermore, their subsidization of energy costs and the high quality energy resources available influence patterns of urban growth at the regional level and encourage these countries to participate in economic activities on the regional and international scales. Therefore, the geographical structure, economic diversification, and regional and international relations of the GCC countries depend significantly on the way in which they secure energy and transform it. One of the main future challenges that faces this region is how to transition to more sustainable energy systems, particularly under water constraints. This transition would require the development of new geographies within the region and globally, and new ways of producing, distributing, and consuming low-carbon energy. Regional power integration and collaboration, and grid extensions, can increase water security and economic integration in the region. Integration and collaboration in the energy sector between the region's countries can be achieved by adopting renewable energy technologies such as large remote sources (i.e., solar, wind, nuclear, tidal) and long-distance transmission through highly decentralized micro-generation or national mini-grids.

Investment in renewable energy can benefit the region by achieving diversification of the sustainable energy supply mix. This is a crucial component of a comprehensive strategy for long-term economic development, ensuring prosperity for the region's population.

A sustainable energy transition can provide tangible concurrent benefits to the region, i.e., long-term economic sustainability and environmental benefits. In addition, it can increase long-term energy security by overcoming the current significant reliance on finite conventional energy resources. The region can also benefit from the ecological transformation process and avoid costly radical changes in the future by preparing for the post-oil era. Investing in the renewable energy sector in this region will create opportunities for capital investments and high-value jobs that can contribute to the full renewable energy chain at different geographical levels (Mondal and Khalil, 2012).

The region can take advantage of its immense potential for solar, wind, and geothermal energy generation. The peak demand in energy resources in this region is synchronized with the maximum global solar radiation in a given year, and the solar potential is estimated to range between 2000 and 2500 kWh/m^2 (Bhutto et al., 2014). Solar PV has high potential in some countries in the region, such as Kuwait, UAE, and Saudi Arabia, because they currently depend mainly on oil for power generation. These countries have little domestic gas production that cannot meet domestic electricity demand. Wind energy has potential in western Oman because of the wind coming from the Indian Ocean. Therefore, integration and collaboration in implementing a sustainable energy mix would allow the region to improve its water and food security by reducing the domestic demand for oil and gas and increasing its exports from these resources for financial gain.

The region is witnessing food trade deficits driven by population growth, economic growth, and limited arable land area, as well a shift in demand from staple to higher-value food products. Although this region is considered food secure, the level of agricultural production per capita is low, and it depends on imports of food commodities from outside the region, which are financed using the high revenues from oil and gas exports. Therefore, managing future food security at the national level must include strategic choices and decisions about securing access to food through a mix of national, regional, and international investments, and potential innovative mechanisms such as virtual reserves. The level of agricultural and livestock productivity various geographically within and between the countries in the region. Countries such as Saudi Arabia, Oman, and the UAE produce more crops than the other GCC countries, but they are far from reaching self-sufficiency. Therefore, integration and collaboration between these countries through regional trade could strengthen food security and balance supply and demand across the region.

The WEF nexus is significant in this regard, as energy and water are crucial components within the food supply chain. As the region depends mainly on imports of food from other countries, its food security is sensitive to the price of energy inputs. The volatility of food prices increases when relying on oil and gas, and this might affect economic affordability and access to food. On the other hand, energy inputs in the food supply chain increase because of the rise in food demand, putting more pressure and strain on the energy system. Although agricultural production in the region meets the food demand of only a small fraction of the population, the region can benefit from using renewable energy and agricultural technological innovation to increase food outputs and to reduce the heavy reliance on food imports.

Another benefit of the WEF nexus in the water and food sectors is the use of virtual water. The region can benefit by importing water-intensive agricultural goods, hence reducing the amount of water used in the domestic agricultural sector, and by allocating this water to other uses in the region. For example, Saudi Arabia became self-sufficient 20 years ago in a variety of agricultural production including some vegetables, wheat, dairy products, eggs, and date palm relying mainly on underground water reserves. However, due the limited annual amount of rainfall, the underground water was not recharged with rainfall and therefore are vulnerable to over-extraction. In an effort to conserve the groundwater resources, Saudi Arabia has phased out wheat and fodder production. Renewable energy can also be used to enhance the agricultural sector. For example, using solar-based pumping solutions is more a cost-effective option than grid- or diesel-based irrigation pumps. In addition, it can mitigate local and regional environmental impacts, reduce government subsidy burdens, support the expansion of irrigation, and reduce dependence on grid electricity.

6. International scale

The benefits of development and progress in WEF security are very unequally distributed between and within countries across the globe. The level of global WEF security is under pressure from national, regional, and international changes, such as economic and population growth and changing lifestyles. On the international scale, WEF security can be achieved through a nexus approach involving integrated management and governance of WEF issues (Hamdy et al., 2016; Zisopoulou et al., 2018). Achieving sustainable management of these three resources will require international collaboration, with fair trade agreements allowing international access to products and benefits.

The Gulf region is rich in energy, which is a significant element for ensuring global food security. It is important at different geographical scales that these energy inputs be decoupled from conventional fossil fuel use, to overcome energy and food cost volatility, minimize energy security risks, and reduce greenhouse gas emissions. These aspects could obstruct international efforts to meet the growing demand for WEF resources. However, global collaboration gives more opportunities to improve access to modern energy services, enhance energy services, and increase the use of renewable energy (Fig. 5). Sharing renewable energy and desalination technologies give more prospects for synergies between countries, regions, and continents, to enhance WEF security and to address trade-offs among these resources.

Different driving forces are leading the transformation of the energy sector globally. Among these forces are rapid adoption of renewable energy, changing patterns of energy demand, and a desire for secure, accessible, and environmentally sustainable supply options. In addition, increasing the share of renewable energy can bring different benefits nationally, regionally, and internationally, in terms of enhancing WEF security, socio-economic development, climate change mitigation, and energy access. Cross-boundary electricity grid interconnections are evolving and may become important in the Gulf region's power generation system.

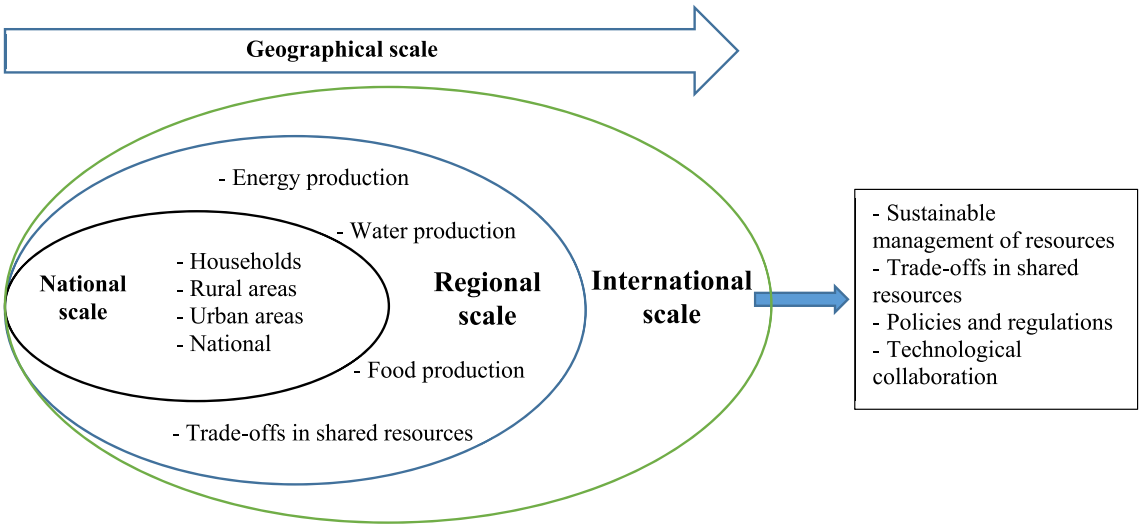

Fig. 5. Geographical framework of the water-energy-food (WEF) nexus at the international scale.

7. Geographical risks to the WEF nexus

Generally, risks to the WEF nexus are associated with certain events, which can have a detrimental effect on security, economic, environmental, and technological issues. These risks have impacts on WEF resources and security at different geographical levels. According to Cutter et al. (2015) and Engel and Strasser (1998), the risks are linked with the process of globalization (global risks) and societal individualization (national risks), which damage the security and stability of the affected region. Risks are events that have considerable detrimental effects for nations and industries over a 10-year period (WEF , 2014).

In this section, we examine the risks affecting the WEF nexus at different geographical scales, and how these risks affect the interdependencies and vulnerabilities among these resources. This can help reveal the impacts and feasibility of resource allocation choices for WEF security. The impact of the national, regional, and international risks on WEF security varies for each of the sectors. Previous studies have identified challenges and risks to WEF resources, but not at different geographical scales (see e.g., de Amorima et al., 2018; Al-Saidi and Saliba, 2019). Among the risks identified in the literature are: population and economic growth risks, environmental and climate change risks, geopolitical risks, energy and food price risks, risks to foreign direct investment in agriculture, systems coupling risks, societal risks, and technological risks, as shown in Fig. 6.

7.1. Population growth

Population growth is one of the main drivers of threats and risks posed by the increased demand for WEF resources at different geographical scales. Each country in the GCC region has experienced rapid population growth during the past three decades, which places more stress on WEF resources and hence more pressure on these sectors at different geographical scales. Population growth in these countries is correlated with increased wealth and high purchasing power, resulting in high consumption. Consequently, the demand for these resources at the national and regional scales becomes acute. Since these countries depend mainly on imports of agricultural commodities, food producers at the global scale encounter greater competition for land, water, and energy and greater negative effects of food production on the environment. This influences the security of supplies across these sectors. Compounded by climate change impacts, this could impair normal socioeconomic functioning, trigger social unrest, and constrain achievement of sustainable development in these countries and the region. Therefore, prudent, intelligent, and integrated management of these resources at the micro geographical scale is critical.

7.2. Economic risk

Rapid economic growth in the GCC countries is driving up demand for WEF resources. Meeting this growing demand is challenging at the national and regional levels. Currently, these countries depend on exporting oil and gas to achieve WEF security, but these resources are limited in nature and their extraction has significant environmental impacts. Global efforts to reduce GHG emissions by reducing the dependence and consumption of fossil fuels will pose an economic risk to these countries and to the region.

Failure of critical infrastructure is another identified economic risk that affects the WEF nexus (de Amorima et al., 2018). Investing in infrastructure at different geographical scales affects key sectors such as WEF production and distribution to the end-user at the national level, and exports to other countries regionally and globally. On the other hand, lack of investment in infrastructure results in degradation of these sectors and services, thereby disturbing economic and social development. Water security is also affected by the not efficient or shortfall of water infrastructure. Not investing in this field has many negative consequences at the

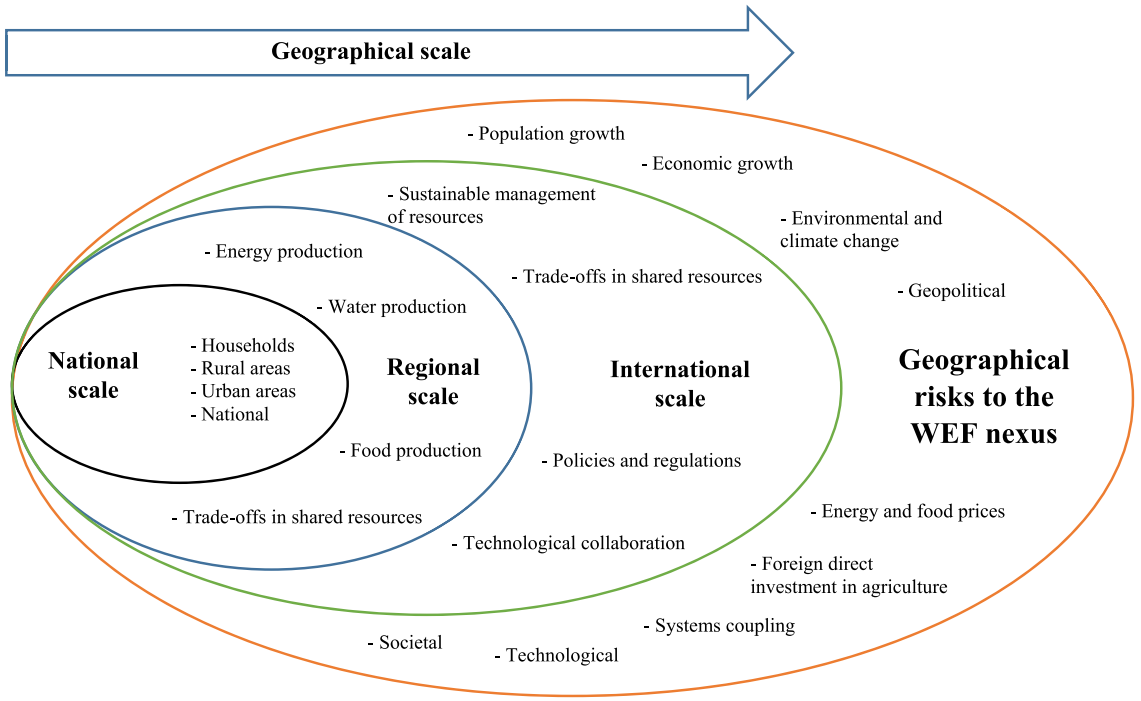

Fig. 6. Risks to the water-energy-food (WEF) nexus at different geographical scales.

national level (OECD, 2014; Dickson et al., 2016; de Amorima et al., 2018). Energy security can be affected by the lack of investment in energy infrastructure resulting in increasing fuel costs, potential debts for consumers, and higher prices of commodities (Vosylius et al., 2013). In addition, infrastructure is significant for food production and processing (Shively and Thapa, 2017).

7.3. Environmental risks

The literature identifies two environmental risks that can threaten the WEF nexus: extreme weather events and failure of effective climate change mitigation and adaptation (de Amorima et al., 2018). At the national level, the IPCC's Third Assessment Report states that arid and semi-arid regions are moderately to highly vulnerable to the impacts of climate change. Assuming continued anthropogenic interference with the climate system over the coming decades, there are likely to be adverse fluctuations in the hydrological cycle, rising sea levels, and changes in the distribution and level of rainfall. These events have potential impacts that can affect the WEF sectors directly. Climate change may result in e.g., increases in the intensity, duration, spatial distribution, coverage, and frequency of heat waves that may range from several days to weeks, higher intensity of precipitation, sea level rise, storm surges, higher intensity of cyclones, and potential changes in the wave regime (Kunkel et al., 2008; Arnell, 2010; SREX et al., 2012; IPCC, 2013; Becker et al., 2013). This will affect the efficiency of water desalination processes and also groundwater quality, by increasing the salinity of coastal aquifers and pollution, and hence increase the level of water scarcity.

Climate change may have significant impacts on coastal transportation infrastructure such as ports and on sea shipping. Ports and other transport hubs/networks are important in the national and international transport network and might be impacted due to long life-time of their infrastructure, their exposed location, and their dependence on trade and shipping. Daily operation of these transportation facilities can be affected by climate change through possible coastal inundation and storm surges that render ports unusable for freight or storage and damage terminals, and thus disrupt intermodal supply chain and transport connectivity, particularly for exporting oil and importing agricultural products. Key vulnerabilities in the GCC countries associated with climate change include heat wave/heat stress. This will result in increasing energy consumption, particularly to operate air conditioning systems (Abulibdeh et al., 2019a).

The Ministry of Energy and the Environment Agency of Abu Dhabi studied different climate change scenarios and concluded that the temperature in the UAE could increase or decrease by the end of the 21st century (Ministry of Energy, 2012). Simulations with output generated at the regional level showed that the UAE will likely experience significant changes in climate conditions in the future, with mean annual air temperature in 2050 and 2100 projected to increase to 1.6–2.9 °C and 2.3–5.9 °C, respectively, compared with the period 1961–1990. The average temperature in the UAE could reach as high as 33 °C by 2100, compared with 27 °C over the period 1961–1990 (Ministry of Energy, 2012). Thus the already hot climate of the UAE will become even hotter, putting additional stresses on a variety of sectors, including the WEF sector.

At the regional level, climate change will impact food security in the Gulf region through various avenues. The availability of water and agricultural output will be directly affected by climate change, while indirect effects will include higher prices for imported

food items and, depending on the type of climate change policies put in place, changes in the price of energy and agricultural inputs. In the arid GCC region, the increase in temperature will have a negative impact on the capacity for generating power and the ability to reliably deliver electricity (EPA, 2016). Furthermore, increasing seawater temperature will reduce the scope for using renewable energy sources such as nuclear power, which requires good availability of cold water to cool the generators.

Globally, the agricultural sector will be severely damaged by climate change through decreased farmland area and less commercially viable output. Owing to its strong dependence on a healthy and balanced natural environment, the agriculture sector is very vulnerable to changes in the surrounding environment due to climate change. For example, heightened temperatures inevitably decrease crop outputs and at the same time promote pest and weed proliferation. In addition, changes in the prevalent rain patterns increase the probability of long-term production declines and short-term crop failure. While certain crops in some regions around the world will benefit from the effects of climate change, the overall effect on the agriculture sector is likely to be negative, which will obviously put global food security in grave danger.

7.4. Geopolitical risk

Geopolitical risk is another factor that may jeopardize the availability and distribution of WEF resources at different geographical scales, and hence jeopardize national, regional, and international WEF security. Geopolitical risk includes, but is not limited to, conflicts at the national, regional, and international levels, failure of national, regional, or global governance, and terrorist attacks.

At the national scale, efforts to safeguard state security influence the security of resource supply, and vice versa. Failure of national governance may result in a lack of integrative WEF resource management, instability of energy distribution, price instability, and prevent the emergence of national policies that achieve food security (Ericksen et al., 2009; Bigas, 2012; Goldthau, 2012). Terrorist attacks can affect WEF resources and security at the national level by damaging water and energy infrastructure, thus interrupting fresh water and energy supplies within the country (Gleick, 2006; Copeland, 2010). Internal conflicts substantially affect energy security by restructuring rural and urban places, increasing the probability of humanitarian disasters, raising nation vulnerabilities, and impacting inhabitants (Cornelius and Story, 2008). In the context of the Gulf region, all these sources of state security threats are present and interconnected. State security threats may also represent a direct risk to resource supply systems (Al-Saidi and Saliba, 2019). Regional and global governance will be affected by “resource war” in the future, particularly with regard to energy resources. Furthermore, any terrorist attacks on energy infrastructure, and oil and gas transport means may have different negative outcomes at all geographical scales, such as interruption of the energy supply (Toft et al., 2010). A recent example is the terrorist attack on two Aramco facilities in Saudi Arabia in September 2019. The attack result in decreasing the country's production of 5.7 million barrels of oil, which is 60% of the country's production. Consequently the world oil price raised by 15%.

7.5. Energy and food prices

The GCC countries rely heavily on international trade through exporting oil and gas to cover the costs of desalinizing water and importing food. This export-import pattern makes these countries extremely vulnerable to price inflation, price risks (affordability of food imports and volatility of import risks), and supply risks (import disruption and the availability of food imports). In addition, it exposes national food and water security to the risk of oil price fluctuation, volatility of import prices, and import disruption. In addition, this structure poses larger questions about economic diversification and transformation. Increasing oil prices results in increasing water prices to the end-user, through increasing the cost of the water desalination process. Another significant factor at the national and regional level is price subsidization polices. Subsidizing WEF prices, as done in the GCC countries, encourages consumers to increase their WEF consumption and the cost to the end-consumer does not reflect the actual cost of generating, producing, transmitting, and distributing these resources. Globally, many countries are vulnerable to price volatility on the global energy market, which may impact food and water prices. Hence, food and water security is increasingly correlated to changes in the availability and price of energy.

7.6. Foreign direct investment in agriculture

The GCC countries have limited agricultural potential and production. Therefore, many of these countries have made large-scale investments in land to outsource agricultural production. These investments enable the countries to reduce the amount of world-price cereals and other agricultural crops that they need to import. However, improper governance has given rise to agricultural outsourcing as a solution to food insecurity. Instead of giving serious attention to proactive adaptation efforts, the GCC governments have adopted an approach that is causing alarm in the international community. Their large-scale investments involve buying or leasing agricultural land for external food production from highly unstable countries, mainly by government-owned and private investors, which is viewed domestically as a politically desirable solution to fulfil the growing local demand for food at considerably lower costs. While importing agricultural products from nations with favorable climate conditions and the necessary technological tools seems to be the sensible option, it is not safe to assume that it is mutually beneficial to outsource the agricultural sector to poverty-stricken nations. For example, poor planning in the country being used for agricultural outsourcing can lead to poorly designed irrigation systems serving large-scale agricultural projects. This can give rise to major consequences such as drying up rivers and disappearing lakes, which creates more major problems in the form of damage to the livelihoods of downstream communities that rely on fishing, grazing, and flood recession farming.

7.7. Systems coupling

Al-Saidi and Saliba (2019) identified system coupling as a major factor that brings both risks and opportunities. In terms of risks, increased coupling between WEF resources can increase the costs of system failure, amplify the requirements for safety, or increase the vulnerability spots at the national, regional, and global levels (Al-Saidi and Saliba, 2019). This is due to a combination of social and economic growth factors and heightened dependency on water-intensive electricity and electricity-intensive water production (Farid et al., 2016; Al-Saidi and Saliba, 2019).

7.8. Societal risk

Societal risk has a prominent influence on the WEF nexus. Failure of urban planning amplifies the challenges that these resources are encountering as a result of the increasing demand due to population growth and climate change. Efficient urban planning at the national level is paramount for providing healthy and nutritious food, fresh water, and energy to the end-user in a growing urban population in the GCC countries. Together with an inclusive food supply system, efficient urban planning is also significant in promoting an effective and efficient network between the urban market and rural producers (FAO, 2015). Substantial amounts of water are needed to supply the demand in urban areas because of the urban lifestyle, population growth, and economic growth. Therefore, unsuccessful urban planning is a critical intimidation to water security. Efficient urban planning is also significant to achieve energy and food security. Population and economic growth in urban areas put more pressure on energy resources, posing potential risks to several areas regionally and globally (IEA, 2012). Intelligent planning is essential to overcome the social challenges caused by the unhealthy lifestyle in urban areas, compounded by climate change and increasing pressure on food resources (Dickson et al., 2016). Handling the interdependence between food security and urban areas is significant to securing sustainable development at the national and international levels (Dickson et al., 2016).

7.9. Technological risk

Adverse consequences of technological advances is another risk to WEF security (de Amorima et al., 2018). In particular, acceleration of technological processes and radical technological transformations may endanger water and food security (WEF , 2016; de Amorima et al., 2018). Emerging technologies may cause significant changes in vital water infrastructure networks. These technologies include biotechnology, geoengineering, artificial intelligence robots, and other Fourth Industrial Revolution (4IR) innovations (WEF , 2017; de Amorima et al., 2018). There are several potential external alterations that can influence the resource supply system's capacity to function at a specific time. These foreign drivers can have a significant influence on the Gulf States, considering their heavy reliance on foreign technology, materials for renewable energies, and supplies associated with food (Al-Saidi and Saliba, 2019).

8. Policy implications

The process of achieving geographical collaboration and integration is not limited to the WEF resources themselves, but extends to the development polices and implications for resources security at different geographical scales (See Fig. 7). It is imperative that development plans and national policies do not merely address the needs of individual sectors. Instead, they should be formulated so as to target the issues in various sectors, which will lead to improved management of trade-offs. In this section, we will focus on policy and opportunities that could be developed and launched in the WEF sectors at different geographical scales.

The GCC countries have increased their capacity for desalination during the last few decades. Although this method is costly for freshwater production, these countries can absorb the cost more easily than other countries, making them less pressured to find alternatives. However, the low FEW scores for water adaptive capacity indicates that it would be challenging to find alternative potable water sources in the case of major disruption such as contamination through an oil spill or nuclear leak in the Arabian Gulf in the future. Therefore, in order to have enough water supply for the ever-increasing water demand in these countries, more emphasis on water demand management is required. This enable providing water in a more efficient and sustainable manner and is consider as a key in reforming water sector policies such as inter- and intra-sectoral coordination, pricing, regulation, water conservation, and better planning. The GCC countries should adopt the integrated water resources management (IWRM) through a fully integrated approach in development, planning, and management of their water resources. The water sector in these countries should be integrated into an over-all plan, including desalinated water, groundwater, and treated wastewater to optimize the usage of each resource for the highest social and economic benefit of each country. To ensure that water resources are used in an efficient and sustainable way, there is a need for an IWRM program that covers demand management, new source of supply, a greater role for the private sector, and institutional and legal aspects. This can reduce the dependence on the desalination water as the main source for potable and industrial supplies and the relegation of the non-renewable groundwater for not useful irrigation of low-value and high water consuming crops.

In managing water demand, water tariff restructuring is essential for water sustainability in these countries. Subsidizing water tariff have negative consequences such as inefficient and excessive water consumption. Water tariff should be set to reflect the real cost of desalinating water but the tariff should not be raised randomly but should come as part of a regulatory impact assessment study so it will not affect the people in need and hence subsidies remain part of the tariff system. Strengthening municipal water tariff system is required to significantly reduce per capita water consumption. This enables enhance demand control measures. Therefore,

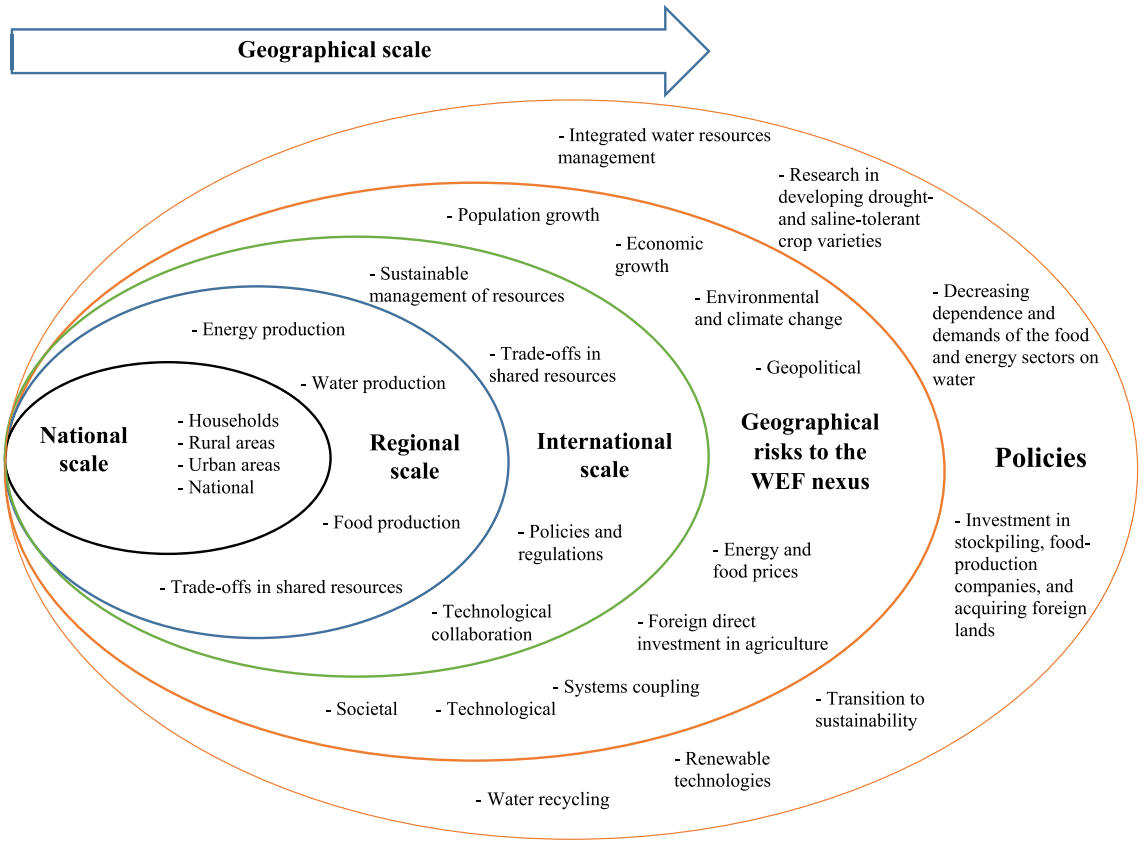

Fig. 7. Geographical policy implications to the water-energy-food (WEF) nexus.

municipal water tariff should be intensively evaluated with an emphasis on the optimality of the tariff structure that aims to achieve water conservation and financial sustainability. On the other hand, water and energy subsidization can be maintained for low-income residents in order to avoid disproportionate financial burdens on them.

Some of the policies that the GCC policymakers can initiate to overcome the water challenges in their countries include strengthening the institutions responsible for water sustainability, increasing the supply of water, and managing water demand. Integrating planning across these sectors at the national and regional levels allows for a systematic analysis of all potential linkage and trade-offs. Building awareness and changing consumer behavior are other important elements of demand management strategy to curb water consumption. The GCC countries have initiated broad efforts in that; however, more efforts is needed using different tools such as media campaigns, conferences and themed workshops, advertising the results of successful pilot projects, and the distribution of efficient water fixtures. Regulatory enforcement and mandatory regulations is other tools to reduce water consumption. These regulations can focus on residential buildings, irrigation efficiency, water-fixture efficiency, the use of grey water recycling, and on sub-metering and leakage detection systems.

The governments in these countries play a significant role in the generation, transmission, and distribution of electricity. Subsidized prices, population growth, and economic prosperity throughout the gulf region contribute to growing energy demand. The GCC countries announced short-to long-term energy efficiency targets to mitigate electricity demand growth. These targets aims to cut peak electricity demand, to reduce overall electricity consumption, and to improve power generation efficiency. Although some countries in the regions (i.e., UAE and Saudi Arabia) have started the first steps towards initiating new policies encouraging renewable energy development, still some visible gaps exist regarding policy mechanisms, institutional regulatory framework, market distortions, capacity building, supply chain, and climate policy. Renewable-based power generation can contribute to wider economic diversification goals in the GCC countries and has the potential to meet their commitments to sustainable development. At the national level, each country announced renewable energy and energy efficiency targets. However, the GCC countries should work collectively to increase the collaboration to achieve the renewable targets at the regional level. Implementing renewable energy policies (such as Feed-In-Tariff (FiT), incentives, quota systems, renewable portfolio standards, and pricing laws) could increase the interest in the renewable energy sector by private investors. Finally, collaboration between the GCC countries and international community in energy sector is significant element to ensure a technological support for renewable energy in the gulf region.

To promote agricultural production, the GCC countries should focus on research in developing drought- and saline-tolerant crop varieties to improve the potential for domestic agriculture by adopting alternative crop varieties. This research started at some countries such as the UAE where the country is experimenting “soilization” in the Al Ain desert. The aim of these experiments is to

test various trees and grass species together based on different water sources such as treated wastewater and groundwater for their reclamation potential. However, limited investment has been made to date in combating desertification through increased land management and forestry. Some of these countries, such as the UAE, are investing and expanding in greenhouse vegetable production and vertical farming in an attempt to improve access to off-season produce and to reduce vegetable price volatility. Furthermore, investments in advanced technology for food production such as brackish high-yield and water-tolerant seed engineering and cultivation is required.

Another area of research these countries may consider is the possibilities for recycling organic food and animal waste to produce "biochar" and similar green fertilizers that could improve fertility of soils, particularly in arid and semi-arid soils. Biochar may provide a permanent improvement in soil quality. Recycling organic food and animal waste back to land can aid to sustain organic matter levels, which leads to improving soil aeration, biological function, nutrient supply, moisture retention, and pollutant attenuation (Arif et al., 2016; Girmay et al., 2008).

Despite the extensive efforts to elevate local agricultural and livestock production, the GCC countries remain heavily dependent on food imports. Therefore, strategies and policies to maintain and facilitate a supply of imported food still significant to these countries. Hence, different policies and strategies can be adapted and implemented in each of these countries or as a region. Among these policies is to invest in stockpiling. Each country can hold large stockpiles of stable grains to mitigate availability risk. However, stockpiling is expensive due to the need to cycle it periodically and because it is exposed to the risk of spoilage. In addition, a limitation of this policy is that it may reduce incentives for private sector participation in the grain market. However, this policy still important in the context of the gulf countries and hence all countries in this region should work collectively to develop agricultural bulk terminal with large capacity to serve the needs of these countries and to reduce the risk associated with importing food. Increasing the physical stockpiles of food located close to population concentration to serve as an emergency supply can create a short-term response to high risk of supply disruption. Establishing regional agreements between the GCC countries to provide emergency food supplies is significant in reducing the amount of stockpiles any of the countries would have to maintain. However, this regional agreement will be less helpful in the event of a risk that affects multiple countries such as regional strife (i.e., the blockade on Qatar by the Saudi Arabia, UAE, and Bahrain).

To avoid the cost associated with stockpiling, the GCC countries can use virtual stockpiling as an associate policy that rely on a variety of financial tools and investments such as an options contract. This tool enable buyers to purchase a certain quantity of grain at a specific price during a specific time. International collaboration is significant in mitigating price risk to the GCC countries. This collaboration can be in the form of developing long-term contracts with different food suppliers instead of purchasing grain on the spot market. The limitation of such policy is that it is less likely to mitigate against availability risk such as a disruption of supply routes.

9. Conclusion

The holistic geographical framework developed in this study addresses the significance of the WEF nexus at the national scale and the importance of integration and collaboration between countries at the regional and international scales to achieve WEF security. The WEF nexus approach is important in the transition to sustainability, by generating benefits that outweigh the transaction costs and reducing trade-offs associated with stronger integration across sectors. Achieving WEF security cannot be attained by each country in isolation from its surrounding neighbors or from other countries across the globe. On the national level, it is a duel responsibility for residents and authorities. Policies that decouple economic and population growth from resource use and enable transition to a more circular economy are essential in order to achieve the sustainability targets in the national visions of the GCC countries.

The geographical framework we present is applicable to other regions world-wide. The Gulf region is rich in energy resources and can use these to secure water and food for its population. Other regions, such as East and South East Asia, which have abundant water and food resources and lack energy resources, could use the revenues from e.g., food exports to import conventional energy resources.

Author statement

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Conflict of interest form

There is no conflict of interest in this study.

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