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Non-conventional water resources research in semi-arid countries of the Middle East

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ABSTRACT

Rapid population growth, climate impediments, poor implementation of regulatory frameworks, and challenging political relations have led to over-exploitation of conventional water resources in the Middle East. This situation may have impelled out-of-the-box thinking and advances in research on non-conventional water resources including desalination, wastewater reuse, rainwater harvesting, and long-distance water transfer. This paper aims to assess the extent of research on non-conventional water resources in the Middle East, and identify original and innovative research findings. Cyprus, Egypt, Israel, Lebanon, the Palestinian Territories, Sudan, Syria, and Turkey were selected for this purpose. A systematic online library search of the scientific literature was conducted, and relations between national indicators and the number of articles and citations were assessed. There was an increasing trend in the number of articles addressing non-conventional water resources. Desalination was the most popular research topic (44%; 5.4 citations, on average), followed by wastewater reuse (37%; 11.5 citations, on average). Publication of desalination articles has increased significantly since 2001, with a substantial number authored by private companies. Non-conventional approaches include commercial salt production at a desalination plant, the strengthening of wastewater reuse standards based on the adverse effects of long-term reuse, the application of a water-harvesting plough for large-scale rangeland rehabilitation, and the development of a 78-km long under-sea pipeline for water transfer. Research on off-site effects and environmental impacts was lacking. Investment in research capacity, as an element of social capital, can contribute to water resources diversification and sustainable solutions both for water-stressed and more humid countries.

Keywords: Non-conventional water; Research; Water scarcity; Middle East

1. Introduction

Five percent of the world's population lives in the Middle East and North Africa regions. Residents of these countries have, however, access to no more than 1% of the world's freshwater [1]. Population growth and expanding urbanization have increased the pressure on limited water resources. Per capita renewable fresh water in the region fell from 4,000 m^3/year in 1950 to 1,100 m^3 today and is expected to drop to

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550 m^3 by 2050 [2]. Besides the population increase, reduction in precipitation as a result of climate change will also exacerbate the situation. Chenoweth et al. [3] reported an about 10% decline in precipitation across the region by both the middle and the end of this century based on results of regional climate model simulations. These authors stated that Turkey and Syria, because of the large agricultural workforces, Iraq because of its downstream location, and Jordan because of its limited per capita water resources coupled with limited options for desalination, will be facing great challenges arising from climate change and the projected precipitation decline.

According to the latest Human Development Report [4], the Arab region, which is the world's most arid, has already water problems that affect more than 60% of the region's poor. The major rivers in this region are transboundary and 66% of the fresh surface water originates outside the region. Using satellite observations, Voss et al. [5] found alarming rates of groundwater depletion in the Middle Eastern countries. Agriculture accounts for the highest water consumption in the region, accounting for around 70% of the total water demand [6]. This notwithstanding, countries in the region are unable to produce sufficient food for its population, importing more than 50% of their total cereal consumption [1].

In addition to climatic challenges, political problems complicate the situation in the region. For example, the average defense expenditure for the years 2004–2010 covered 4–7% of the GDP of Israel, Sudan, and Lebanon, while it was less than 2% for European countries like Spain and Italy, according to the World Bank [7]. The Middle East has a number of countries whose political perceptions and actions are not aligned or in conflict with their neighboring countries or with the international political mainstream and do not have sustainable, co-operative agreements on sharing their transboundary water resources [8,9]. Gunasekara et al. [10] classified most of the countries of the Middle East as highly vulnerable for water-conflicts.

In the Middle East, depletion of conventional water resources and political complexities may have propelled out-of-the-box thinking and advances in non-conventional water resources research. UNESCO [11] reported that expansion of non-conventional water resources has become an important response to water scarcity in the Arab region. Non-conventional water resources that are used in this region include desalinated seawater, rainfall-runoff water captured by water harvesting, marginal quality water, freshwater obtained through long-distance transportation, and virtual water obtained through food trade [12]. Non-conventional water resources supply 20–55% of Israel's total water demand, while this can be up to 10% for other countries in the region [6]. The Israeli government agreed to double the desalinated water production by 2020 and a similar strategy is being followed by the Cypriot government [13,14]. Syria reportedly uses 90% of its treated and untreated wastewater in agriculture, according to the FAO [15].

The objective of this paper is to assess the extent of non-conventional water resources research in the Middle East and identify original and innovative research findings. Desalination, wastewater reuse, rainwater harvesting, and long-distance water transfer are the non-conventional water resource practices analyzed in this paper. A subset of countries, covering the divided island of Cyprus, Egypt, Israel, Lebanon, the Palestinian Territories, Sudan and South Sudan, Syria, and Turkey, which are sharing surface and groundwater resources were selected for the research.

2. Methodology

The research methodology is schematically depicted in Fig. 1. Key word searches were conducted in the ISI-Web of Science electronic library database (upto December 2012) to find articles about non-conventional water resources in the selected countries. As search terms, the country names with a combination of different keywords for each non-conventional water resource practices were used:

Desalination: *Country name* AND (desalination OR desalting OR desalinisation).

Wastewater reuse: *Country name* AND ("sewage water" OR "marginal quality water" OR "waste water" OR wastewater OR "treated sewage" OR "recycled water" OR "drainage water") AND reuse.

Water harvesting: *Country name* AND ("water harvesting" OR "rainwater harvesting" OR "runoff farming" OR "runoff harvesting" OR "desert agriculture").

Water transportation: *Country name* AND ("water transport" OR "water transfer" OR "water export" OR "water import" OR "pipeline" OR "medusa balloons" OR "trans basin").

After the search, the abstracts were read and articles that did not deal with non-conventional water resources, for example, articles on oil and gas pipelines, were eliminated. The remaining articles were exported to the Refworks literature database. Articles that covered more than one country were counted for all countries.

The number of citations to each article and the locations of first author affiliations were recorded. The number of citations measures the popularity of an article, which indicates several factors such as

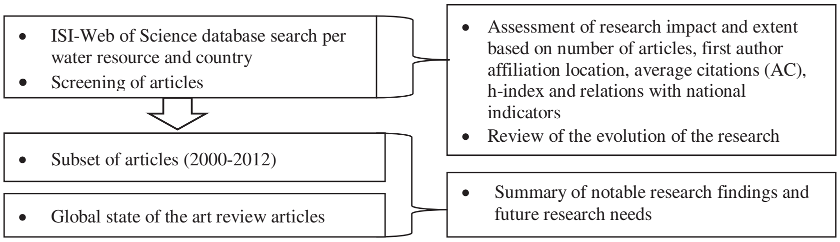

Fig. 1. Schematic overview of research methodology.

importance of findings, dissemination success, crowdedness of the particular scientific field, popularity of the subject of the article, and persistence (an article that gets cited once is more likely to be accessed and then cited by someone else) [16]. First author affiliations were classified as foreign or domestic to assess the in-country research capacity. Average citations (AC) per water resource were calculated. The *h*-index was also used as a capacity and quality indicator of a country. The *h*-index is normally used for measuring the quality and productivity of published work of a scientist [17]. A scientist with an index of *h* has published *h* papers, each of which has been cited in other papers at least *h* times. In this work we computed the *h*-index per country and per non-conventional water resource, meaning there were *h* non-conventional water articles in a country cited more than *h* times. The *h*-index does not include articles with a low number of citations and can be used as a research capacity indicator when the number of articles is relatively large. To obtain a better understanding of the evolution of the research needs and directions, the changing number of publications for the different non-conventional resources was plotted over time.

Country-based economic (GDP per capita), academic (expenditure on education, total number of published journal articles), and water resources (renewable water resources per capita, total non-conventional water production) indicators were used to assess the relations between these factors and non-conventional water resources research. Information on water resources was obtained from Aquastat, FAO's global information system [15], while economic and academic indicators were obtained from the World Bank [7]. For the purpose of this review, the data for Sudan and South Sudan, which became independent in July 2011, were not disaggregated. Country names in the key word search for Sudan included Sudan and South Sudan and for the Palestinian Territories, Gaza and West Bank.

Lastly, to identify novel research findings, all articles that were published in or after the year 2000 were reviewed. The research findings of the selected countries were placed in a more global perspective through a comparison with findings from global studies, results from other regions and state of the art reviews. Finally, recommendations for future research directions were extracted.

3. Results and discussions

3.1. Non-conventional water resources research and development

The total number of non-conventional water articles, the first author affiliation location ratio (domestic over total), the average number of citations, and *h*-index per territory and per resource are presented in Table 1. A total of 433 non-conventional water resource articles were found for the selected territories (see auxiliary material for the full list). Desalination was the topic of 44% of the articles, and 37% of the articles dealt with wastewater reuse. However, the *h*-index indicated that the wastewater reuse articles were better appreciated than the desalination articles. The highest percentage of domestic first author affiliation was for wastewater reuse articles with 78%. Water transfer articles contributed only 6% of the total articles and 76% of these articles had a foreign first author affiliation location.

Israel had the highest number of articles followed by Egypt and Turkey. Sudan and Syria had the lowest number of articles and 70% these articles had a foreign first author affiliation location. This indicates that these countries have low research capacity or limited research interest in the area of non-conventional water resources. In Cyprus, Egypt, and Israel, the majority of the articles were about desalination. Cyprus' and Israel's high number of desalination articles could be related to a higher GDP and lower renewable water resources per capita than the other countries (Table 2), making the relatively expensive desalination technology an attractive source of water. In Lebanon, the Palestinian Territories, and Turkey, wastewater reuse

Table 1
Non-conventional water resources research indicators

Resource	Cyprus	Egypt	Israel	Lebanon	Palest.	Sudan	Syria	Turkey	Total
Desalination									
Articles (#)	35	53	66	5	12	1	2	17	191
Domestic first author aff.[a]	0.49	0.64	0.82	0.60	0.67	0	0	0.88	0.69
Average citation	5.1	5.8	6.2	3.2	3.2	1	1.5	4.7	
h-index	7	11	10	2	3	1	1	5	15
Wastewater re.									
Articles (#)	13	25	61	9	14	1	4	36	163
Domestic first author aff.	0.77	0.64	0.92	0.44	0.71	0	0	0.86	0.78
Average citation	17.6	5.6	11.7	17.3	11	0	38	9.3	
h-index	6	9	15	4	3	0	3	8	19
Water harv.									
Articles (#)	0	4	31	1	4	8	5	1	54
Domestic first author aff.	0	0.50	0.68	1.00	0.50	0.25	0.40	0	0.55
Average citation	0	0.7	10.9	5	7.5	4.2	1	0	
h-index	0	1	10	1	3	4	1	0	13
Water transfer									
Articles (#)	4	2	4	1	1	1	1	11	25
Domestic first author aff.	0	0	0.25	0	0	0	0	0.45	0.24
Average citation	4.2	3.5	16.7	1	1	0	15	2.8	
h-index	1	2	2	1	1	0	1	3	5
Total									
Articles (#)	52	84	162	16	31	11	12	65	433
Domestic first author aff.	0.52	0.62	0.81	0.50	0.64	0.18	0.17	0.78	0.68

[a] The number of articles with a domestic first author divided by the total number of articles.

Table 2
National indicators and number of non-conventional water resource articles

Country	Population[a] (10^6)	Renewable water resources[b] (m^3/inhab/year)	Dependency ratio[b,c] (%)	GDP per capita[a] (US$)	Military expenditure (% of GDP)	Total scientific and technical articles[a,d]	Non-conventional water resource articles
Cyprus	1.1	698	0	30,670	2.0	1,485	52
Egypt	82.5	694	97	2,781	2.4	36,067	84
Israel	7.8	235	58	31,282	7.0	144,203	162
Lebanon	4.3	1,057	1	9,413	4.3	3,131	16
Palest. Ter.	4.0	201	3	1,123	NA	NA	31
Sudan	34.3	1,445	77	1,435	4.2	1,322	11
Syria	20.8	808	72	2,893	4.2	1,227	12
Turkey	73.6	2,857	2	10,524	2.4	87,793	65
Italy	60.8	3,147	5	36,103	1.8	26,755	101
Spain	46.4	2,400	0.3	31,943	1.3	21,543	209

[a] Latest numbers from the World Bank [7], note that the year of the data can vary per country.

[b] Latest numbers from the Aquastat [15], year of data can vary per country.

[c] Percentage of total renewable water resources originating outside the country.

[d] Total number scientific and technical articles published between the years 1985 and 2009.

research had the highest number of articles. In Sudan and Syria, water harvesting articles were more than the number of articles on the other resource technologies. This might be related to the relatively low investment cost of water-harvesting techniques, considering that Syria's and Sudan's GDP per capita is relatively low. There were no articles on water harvesting from Cyprus.

Table 2 presents the national indicators that could have influenced non-conventional water resource research. No clear relation between the indicators and the number of non-conventional water resource articles were found. However, there were some notable findings. Cyprus had the highest per capita article ratio with 47 non-conventional water resources articles per million people followed by Israel with 20 and the Palestinian Territories with 8. This indicated that both water scarcity and economic capacity could have stimulated non-conventional water resources research. The total number of published scientific and technical articles is an indication of a country's research capacity, and the percentage of non-conventional water research articles from this total can be used to compare the capacity and interest of a country in non-conventional water resources research with other scientific domains in the country. This non-conventional water resources research percentage was highest in Cyprus with 3.5 followed by Syria with 0.9 and lowest in Israel and Turkey, both 0.1.

Ren et al. [18] found that the eight most prolific water resources management publishers in the Web of Science online library database between 1990 and 2012 were USA with 2,224 papers, P.R. China with 1,607, Australia with 716, UK with 641, Germany with 515, Canada with 487, India with 381, and Spain with 380 papers. Despite the water related challenges in the Middle East, none of the Middle Eastern countries made it on this list. More specifically, Sowers et al. [19] concluded in their study on climate change, water resources, and the politics of adaptation in the Middle East and North Africa that the countries in this region have limited scientific capacity to conduct local research on water and climate. They pointed out a host of interrelated factors that hamper scientific research in the region such as security concerns, limited cross-border cooperation on water issues, military control over data access, political constrains, limited investments, inadequate compensation, and emigration of scientists.

Fig. 2 shows the number of water reuse articles vs. annual water use per capita from treated municipal wastewater and the number of desalination articles vs. total annual water use from desalination. There were no comparable data on water use per country from water harvesting and water transfer. Data on desalination for the Palestinian Territories, Syria, and Lebanon were available at DesalData [20] and for Sudan, Turkey, Cyprus, Egypt, and Israel, the data were obtained from Aquastat [15]. There were no data for Sudan about treated wastewater reuse in Aquastat, neither in the literature in general, therefore it was assumed to be zero. A positive relation between the number of articles and the resource could be observed.

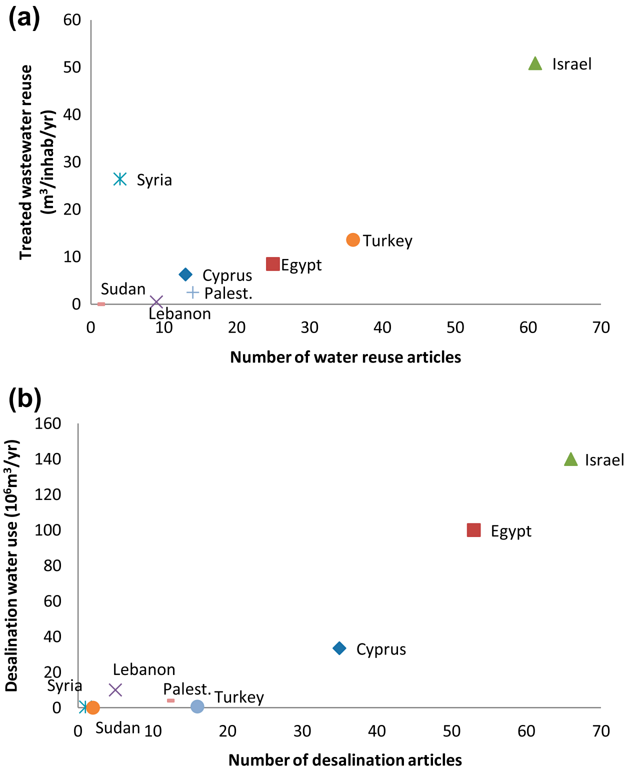

Fig. 2. Relations between number of desalination articles and desalinated water production (a) and number of waste water articles and treated wastewater reuse (b).

The evolution of the number of non-conventional water resources research articles over time is presented in Fig. 3. There was an increase in the number of articles for all resources over time. Since 1981, desalination articles in the region were published at a rate of 1–4 articles per year up to 2001 when a sharp increase occurred. The increase in the number of water harvesting and water transfer publications was less substantial than for wastewater reuse and desalination.

Israel's pioneering role in non-conventional water resources research among the selected countries became apparent when we scrutinized the research evolution over time. Israel was the object of 67% of the desalination articles published until 2001. The increase of the desalination articles in 2001 was mainly caused by the contribution of Cyprus (40%) and Egypt (32%), while there were no desalination articles from Cyprus until that year.

Private sector involvement in the increase of the number of desalination articles in 2001 was notable as one third of the articles published in the selected

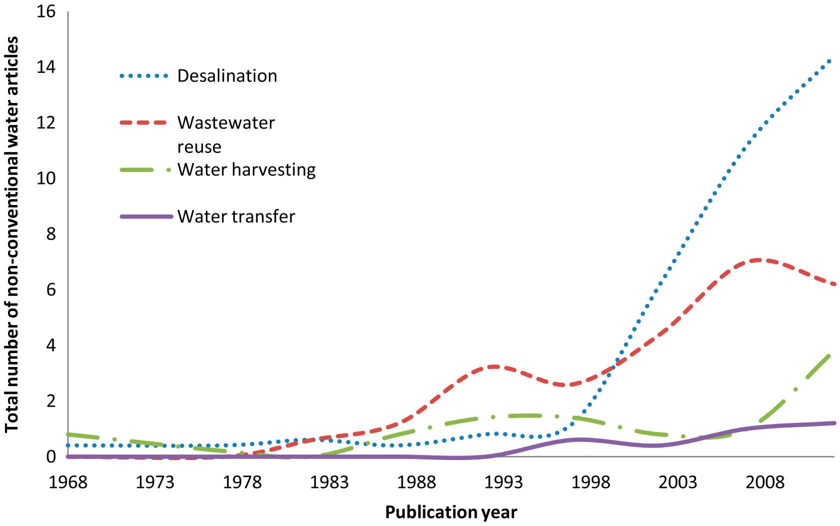

Fig. 3. Number of non-conventional water resources research articles over time (five-year moving average).

countries in this year were authored by private companies. Also, between the years of 2000 and 2012, four articles from the top 10 most highly cited articles were authored and another four were co-authored by private companies. This might be because most articles were about technological advances, which needs substantial economic capital (e.g. experimental results from pilot plants).

Israel was the focus of 74% of the wastewater reuse articles between 1978 and 1994. However, Israel's share in wastewater reuse articles dropped to 26% between 2009 and 2012. This was not only because Israel did not publish as many wastewater reuse articles as before but also because other countries in the region started to publish more wastewater reuse articles. Israel was also the topic of 89% of the rainwater harvesting articles between 1962 and 1995. Several countries started to publish on rainwater harvesting in the region after 1995.

The development of Israel's water resources strategies, described by Tal [21], followed a similar trend as the publication of research articles. He reported that Israel was the first country in the world to set standards for wastewater reuse in 1953. Long-distance water transfer became a strategy in 1964 when the "National Water Carrier" project was completed to carry water from Lake Kinneret in Israel's relatively wet northern region to the drier south of the country. Starting in the 1980s, a network of 178 reservoirs was established across the country in order to collect rainwater runoff mostly in semiarid and hyper-arid regions. The Israeli government decided to build five new desalination plants in 2002 when desalination became more economical. Israel's continuously evolving water resources development and management process has resulted in a combined strategy of water transport, rainwater harvesting, wastewater reuse, and desalination.

3.2. Research findings

3.2.1. Desalination

Elimelech and Phillip [22] suggested in their global review that despite major improvements in desalination technology, energy consumption of these technologies is still higher than that of other conventional fresh water treatment technologies. A number of highly cited articles in our selected countries reported that between 25 and 70% of the price of desalinated water was attributed to the energy cost [23–25]. This wide range indicates, besides differences in the various cost categories in the different countries, also that energy efficiencies can still be optimized.

Solar energy for seawater desalination was a popular topic in almost every country in the region. Abu-Jabal et al. [26], Fath et al. [27], Audah et al. [28] and Nafey et al. [29,30] were the highest cited articles, with an average of 22 citations, which investigated solar energy for seawater desalination. As Nafey et al. [30] explained, solar desalination technologies employ two types of solar energy collector systems; direct and indirect. Direct collection systems use solar energy directly to produce distillated water. Indirect collector systems combine solar energy collection systems with conventional desalination systems, such that solar energy is used either to generate the heat required for desalination and/or to generate electricity to provide the required power for conventional desalination plants. Articles concerned with both [26–32] solar desalination systems were present in our region of investigation.

Li et al. [33] investigated solar assisted desalination plants around the globe from the USA to Europe and from the Gulf Countries to India in their recent review. They concluded that most current solar desalination systems are indirect solar desalination systems. These systems are relatively expensive and their performance depends on location, weather, and season. They found that hybrid solar/fossil desalination systems are more economical and could overcome the intermittence of solar energy. Economic investigations of such solar/fossil hybrid desalination systems were not present in the journal articles of the selected countries. Lamei et al. [32] concluded that for indirect solar desalination plants, photovoltaic systems were more costly than solar thermal systems. They reported that solar thermal costs (0.06–0.09 US$/kWh) were similar as local energy prices at the time in Egypt, but photovoltaics are more suitable for small- to medium-sized projects (capacity of up to 15,000 m^3/d) in remote areas.

Competition for socially and economically important coastal land, damage to the marine environment, increased use of energy, damage to underground water (in the case of Gaza strip where brackish groundwater is desalinated), and noise pollution were reported as the negative aspects of desalination in the selected countries [34–40] reviewed articles around the globe on environmental aspects of desalination, and concluded that a large proportion of the published work was descriptive and provided little quantitative data. This was also the case in the selected countries in our study region.

An interesting case study about the environmental damage caused by desalination units was presented by Assaf [34] and Baalousha [36]. They reported that in the Gaza Strip, six reverse osmosis desalination plants, owned by government authorities, and many small desalination units, owned and operated by private investors for commercial purposes, use brackish groundwater instead of seawater for desalination due to economic advantages. They suggested that abstracting brackish groundwater from beneath fresh groundwater lenses might contribute to a loss of fresh water resources and increased intrusion of seawater into the fresh water aquifers. Effluent from these desalination plants is not regulated and is disposed in nearby fields, causing further groundwater contamination [36].

Quantitative studies about environmental aspects of desalination were conducted by Drami et al. [41] and Abd el Wahab and Hamoda [39]. Drami et al. [41] studied the effects of the brine discharge from the Ashkelon seawater reverse osmosis plant (Israel) to the Mediterranean, and identified effects of the discharges on water quality and neritic microbial community. Temperature increase due to the discharge ranged between 3.2 and 7.3°C and salinity increase at the discharge location reached 1.6 parts per thousand, compared to the background levels. They reported that nutrient concentrations were higher at the outfall, while phytoplankton densities were lower. They found that chlorophyll-*a* and picophytoplankton cell numbers were negatively correlated with salinity, but more significantly with temperature up to a distance of 1,340 m from the discharge location.

Abd el Wahab and Hamoda [39] found increased salinity and increased temperature close to the discharge unit of a desalination plant in the Red Sea in Egypt. They reported that salinity of the discharged water ranged between 50 parts per thousand to 68 parts per thousand and caused an increase of up to 1.5% in mortality for planktonic larvae, at the discharge location. They also detected chemical pollutants such as chlorine, antiscalants, and heavy metals.

An interesting case of handling brine was presented by Ravizky and Nadav [42] from Israel where brine was used for high-quality table salt production. The brine from the desalination plant was blended with seawater and fed to a series of evaporation ponds before entering the salt processing factory. Brine discharge line expenses were spared by the desalination plant and damage to the marine environment was prevented. In addition, salt production of the company was increased by 30%. This case is also a good example of co-operation between the government (desalination plant) and private sector (salt production company), where electric power bills and the investment in the intake and the supply of piping were shared.

3.2.2. Wastewater reuse

Water scarcity has driven farmers to use untreated or poorly treated sewage water for irrigation, as reported in studies in Cyprus, Egypt, Israel, Syria, and Turkey [43–50]. This has given rise to various concerns and has motivated research on the effects of sewage water on crop yields, soil quality, and human health.

There are articles investigating various aspects of the use of effluents from primary, secondary, and tertiary level wastewater treatment plants. The literature in the region revolves around pros and cons of using effluents of different levels of treatment with continuous improvement of standards of wastewater reuse. According to FAO [51], the objective of primary treatment is to remove organic and inorganic solids and scum (floating material) by sedimentation and skimming. Some organic nitrogen, organic phosphorus, and heavy metals associated with solids are also removed, but colloidal and dissolved constituents remain unchanged. The secondary treatment aims to further treat the effluent from primary treatment to remove the remaining organics and suspended solids. It removes biodegradable dissolved and colloidal organic matter with aerobic biological treatment. Tertiary wastewater treatment includes individual treatment processes that are necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals, and dissolved solids.

The identification of pollutants and pathogens in wastewater and the formulation of standards for its reuse have been part of a continuous trial and error process in the region. Israel has been a pioneering country for wastewater reuse as it started setting standards in the early 1950s [21]. After health concerns and the improvement of treatment technologies, new standards for secondary treatment facilities were set by national law in 1992. Following a regulation that limited the boron and sodium content in detergents in 1999, Israel further limited the concentration of salts in all industrial effluents by the national water law in 2003 [52]. The average concentration of chloride and boron in sewage water reaching the treatment plants has declined 50% after the introduction of the law. These improvements were still not sufficient for the sustainable reuse of the wastewater and several studies have suggested partial desalination of treated wastewater to prevent salinization of land and water [53,54].

Secondary treatment standards proved to be inadequate in other countries as well for several reasons. Firstly, the range of crops that can be grown at this treatment level is relatively narrow because of the presence of pathogens in the effluents and secondly, the salinity in the wastewater posed risks to soils and freshwater sources [21,55,56]. Heavy metals, originating from wastewater reuse as irrigation, were also detected by a number of researchers in the region. Cobalt contamination of soils due to wastewater reuse for irrigation was reported in Egypt [57], and lead, cadmium, and chromium were detected in rice plants in Turkey [58]. Levy [50] reviewed field and laboratory studies on the effect of treated wastewater use on soil properties in the past 15 years in Israel. He reported that treated wastewater can enhance clay swelling and dispersion in soil, resulting in increased clay depletion from the upper soil layer, deterioration of aggregate stability, decreased soil hydraulic conductivity, and increased soil susceptibility to seal formation, runoff, and soil erosion. Wallach et al. [59] also reported severe soil water repellency in the top 5 cm of the soil and preferential flow paths in the soil profile, in a 20-year long wastewater irrigated field in Israel.

Based on the above experiences, Israel and Cyprus have set stricter and more detailed guidelines for wastewater reuse, than the 1989 guidelines of the World Health Organization (WHO) [21,55,60]. Both countries have set standards for different groups of crops. Israel now targets nationwide tertiary treatment, while Cyprus prescribes secondary or tertiary treatment, both with infection, or long-term (more than 60 d) stabilization ponds [21,55]. On the other hand, the WHO recognized that low- and medium-income countries had difficulties achieving their 1989 standards and proposed a radically new approach in 2006 [61]. The 2006 WHO guidelines are based on a risk assessment and management framework that shifts the focus from water quality thresholds to manageable health risks.

An important property of wastewater is its nutrient content, which decreases with increasing levels of treatment. Papadopoulos and Savvides [48] and Kiziloglu et al. [62] found higher yields for crops irrigated with untreated, primary- or secondary-treated wastewater, compared with yields of groundwater-irrigated crops. However, neither of the studies analyzed microbiological pollution. Furthermore, Kiziloglu et al. [62] found that the heavy metal content of the irrigated vegetables was significantly affected by the wastewater irrigation. Another aspect of wastewater irrigation was highlighted by Fine and Hadas [63]. They suggested that secondary level treatment can provide six times more greenhouse gas emission abatement potential (e.g. CO_2-eq m^{-3}) than tertiary treatment, because less manufactured fertilizers are needed due to the preservation of the wastewater's value as a fertilizer. Although the fertilizer value of wastewater can be beneficial as suggested by the aforementioned papers, excessive or imbalanced nutrient applications can cause undesirable vegetative growth, delayed or uneven maturity, and reduce crop quality and pollute groundwater and surface water as reported by Qadir et al. [64]. These authors also suggested that long-term studies on these issues are rare and that farm-level monitoring to adjust fertilizer or sewage irrigation rates is generally lacking.

Tertiary treatment reduces the nutrient content of the wastewater for irrigation but may still not be sufficient to prevent soil and groundwater pollution. Several articles from the selected countries investigated the fate of emerging contaminants such as pharmaceutical and endocrine-disrupting compounds in advanced secondary and tertiary treated wastewater [65–67]. Zoller [67] detected endocrine disrupting compounds of polycyclic aromatic hydrocarbons and alkylphyenol ethoxylates in the rivers/streams and groundwater bodies of Israel originating from tertiary treated wastewater used for irrigation. He concluded that irrigation with wastewater is not sustainable since it poses ecotoxicological and health related risks. Kfir et al. [68] also emphasized the need for regulations for hormones and antibiotics present in tertiary treated wastewater effluent. Fatta-Kassinos et al. [69] stated in their review article that there is a lack of knowledge on the accumulation of heavy metals and other elements in the soil, and on uptake by crops arising from irrigation with tertiary treated wastewater.

Technological improvements in wastewater treatment have been made over time. Similarly, identification and quantification of a number of compounds in treated wastewater has improved with the technological progress in analytical chromatographic methods. The number of studies focusing on the analysis and the toxicological assessment of such compounds in treated wastewater, crops, and the environment is expected to increase globally. In our selected countries, the studies on wastewater reuse in early years started with investigations on bigger molecules in abundance (pathogens, nutrients, and salts) and in more recent years, with the advancement of chromatographic technology, studies focused more on smaller molecules and trace elements (heavy metals, pharmaceuticals, and endocrine disrupters). It became clear from our literature review that the favorable conclusions for wastewater reuse become less favorable with the advancement of chromatographic technology. There is definitely a need for further research on the ways of retaining the nutritional value of wastewater while reducing the levels of undesired contaminants to acceptable levels.

3.2.3. Water harvesting

Water harvesting technologies include micro-catchment water harvesting for crops, trees or shrubs; macro-catchment water harvesting for small surface water reservoirs or groundwater recharge and rooftop water harvesting for household or garden use. Water harvesting has a long tradition in the arid and semiarid countries of the Middle East. Runoff farming, micro-catchments, and cross-channel terraces have supported agriculture throughout the ages in the Negev desert, dating all the way back to the 6th millennium BCE [70]. Various studies have analyzed the functioning of such ancient water-harvesting systems in our study countries [70–73]. Field research in the Negev during the 1960–1980s found that wheat, barley, grapes, and other crops can be grown in areas that receive only 85 mm of average annual rainfall. Basic requirements for such systems are (i) a runoff contributing area with high runoff potential, (ii) a topography to sustain runoff flow to terraced agricultural fields in the valleys, and (iii) deep soils with good water holding capacity (e.g. silt–loam) [70,74]. Avni et al. [74] used optically stimulated luminescence dating of sediment and found that water harvesting structures were developed both in the Iron age (ca. 2700 BCE) and in the late Roman and early Islamic periods (200-900 CE). Berking et al. [72] applied a rainfall–runoff model (HEC–HMS) to estimate the surface runoff flowing to the water-harvesting reservoirs in the ancient cities of Naga, Sudan, and Resafa, Syria. They found that these reservoirs could still be filled today.

There are also great expectations for water harvesting to improve food security for our growing world population. A global vegetation and water balance modeling study indicated that if 25% of runoff could be harvested and applied as irrigation during periods of crop water stress, net primary productivity could increase by 11% [75]. Similarly, Wisser et al. [76] found that water-harvesting reservoirs in low-yield areas could increase global wheat production by 20–38%. However, these studies indicated that the majority of these gains are made in humid environments with highly seasonal rainfall, while the potential for production increase in the drier areas of our study region are much more limited.

A method for ranking potential sites for small water-harvesting reservoirs has been developed by El-Awar et al. [77]. The method includes an Analytic Hierarchy Process and an interactive participatory approach was applied to make use of local farmers' experience. The method was successfully applied to an agricultural area along the western slopes of the anti-Lebanon mountains, with an average annual rainfall of 300 mm. In central Sudan, the construction of a dam on a seasonal stream to protect Gadarif city against floods was found to provide a new source of groundwater recharge [78]. This unexpected result led to the building of four more recharge dams.

Two water-harvesting studies in even drier environments in Syria focused on surface runoff in micro-catchment systems. Bruggeman et al. [79] analyzed surface runoff in a highly sloping olive field (8–15% slope) in an area with a long-term annual rainfall of 210 mm. They found that the harvested water could replace one or two irrigations (121–150 L/year), but that the efficiency of the micro-catchments was constraint by the limited depths of the soils. Ali et al. [80]

constructed 5,000 micro-catchments with the help of a special tractor-pulled plow in a degraded rangeland environment, with an average annual rain of 111 mm. The catchments were planted with shrub seedlings. They found that surface runoff on the slightly sloping land (2–5%) ranged between 5 and 85% of the annual rainfall, with an average value of 30%. However, no farmer field studies have been published during 2000–2012 that analyzed the effect of water harvesting on changes in productivity in our study countries.

Water supply shortages are widespread in the Palestinian Territories, which seems to have motivated a number of rooftop water-harvesting studies [81,82]. Al-Salaymeh et al. [81] found that 65% of the households in Hebron had a cistern for rainwater harvesting or for water storage from other sources. The authors sampled 100 cisterns and found that 95% of the samples was contaminated with total *Coliform* and 57% with *faecal Coliform*. This renders the water unacceptable for drinking purposes, even though all users indicated that they used the water for drinking. The authors concluded that it is imperative that the harvested rainwater should be disinfected (e.g. via chlorination). They also recommended the cleaning of cisterns and water-harvesting surfaces and to divert the dirty water of the first season storm or the first few millimeters of each storm away from the cistern. Similar findings were reported by Meera and Ahammed [83] in a review study on the quality of rooftop water-harvesting systems. These authors reported that microbiological contamination was found in most studies, unless special care was taken during collection and storage of the harvested water. Lange et al. [82] found in a survey of 500 households in Ramallah that 40% of the households had a water-harvesting reservoir, but that one third of those were out of use. These results seem to contradict with those obtained as part of a comprehensive life cycle impact assessment study by Nazer et al. [84]. These authors found that 85% of 244 survey participants were willing to pay for a water-harvesting reservoir. Lange et al. [82] used a 1-parameter model to analyze potential rainwater-harvesting volumes. They found that urban rainwater harvesting provides a relatively small contribution to overcome water scarcity in the region and decreases significantly during droughts. However, its importance should not be overlooked as it is a sustainable, local water resource.

Regulations and incentives that foster the use of urban rainwater systems are increasingly being developed worldwide. In Catalonia (Spain), more than 40 municipalities have approved local regulations that promote the use of rainwater harvesting [85]. An example of such regulations is a building code that mandates the installation of rainwater-harvesting systems for buildings with a garden area of more than 300 m^2. A user survey in one of these municipality indicated that both regulations and subsidies are good strategies to advocate and expand rainwater-harvesting technologies in residential areas. The harvested water is mainly used for landscape irrigation but also for toilet flushing, cleaning, and swimming pools.

3.2.4. Water transfer

Turkey's per capita renewable water resource is highest among the selected countries and this is reflected in the international water transfer studies, as almost half of the articles were about Turkey. Gruen [86] examined political strategies employed by Turkey to foster regional peace by exporting water from Turkish rivers to Cyprus, Israel, the Gaza Strip, Jordan, and other Arab countries. Moreover, Kohn [87] assessed the managerial aspects of possible water shipping from Turkey to Cyprus, Israel, Jordan, and Arab countries and concluded that this trade could not only foster an efficient allocation of a scarce resource across and within countries but could also establish a highly visible market price for water. However, Elkiran and Ongul [88] reported that the transfer of water from Turkey to Cyprus between 1998 and 2002 (4.1×10^9 m^3 in 5 years) in so-called medusa balloons pulled behind tankers was costly (upto \$0.33/m^3) and could not meet the required needs.

More recently, Turkey started the construction of a 78 km long undersea pipeline, which is expected to transfer 75 million m^3 of water per year from Turkey to the occupied north of Cyprus [89]. Numerical simulations that investigated the vibration and instability of the suspended undersea pipeline indicate that all cases with different forces and modes are in an unstable state [89,90]. The authors recommend that some engineering measures must be considered. Furthermore, no academic studies have been published that assessed the potential to recover the environmental, resource, and financial costs of this water supply, as required by the European Water Framework Directive.

There were also several articles about water transfer within the national borders [21,91,92]. Tal [21] presented managerial aspects and water quality issues of water transfer from northern to southern Israel, which has increased the cultivated area and agricultural production. He reported that high salinity (390 mg/L) and turbidity levels of the transported water have caused soil and groundwater pollution. He also noted that experts and environmentalists advocate the decommissioning of the pipeline because of the long-term salinization damage and steady drying of the

Dead Sea (an average drop in water level of 1.2 m/year) due to the water deprived of the Jordan River for the pipeline. Lamei et al. [92] compared the economic aspects of long-distance water piping from the Nile to reverse osmosis desalination for the tourist city of Sharm El Sheikh at the Red Sea in South Sinai, Egypt. They found that unit capital costs for pipelines longer than 140 km are higher than a reverse osmosis desalination plant at any flow capacity. Unit production cost of a desalination plant are lower than long-distance piping when the length of pipelines are 300 km or more and the capacity is equal or more than 2,000 m^3/d. Hussein and Awad [91] proposed several developments, including groundwater recharge and long-distance water transfer, as part of an integrated water management plan for Eastern Sudan. They suggested piping water from the River Atbara to a natural watercourse from which it can flow by gravity to the Delta for irrigation with minimal costs.

4. Conclusions and recommendations for further research

The number of articles on non-conventional water resource technologies in the selected semi-arid countries in the Middle East increased from two articles per year in the 1980s to more than twenty in the first decade of 2000. During the same time, the share of non-conventional water resources research articles in all scientific and technical journal articles in the selected countries increased also from 0.4 to 1.5% [7]. The increase in the number of desalination and wastewater reuse articles was more drastic than that of the transfer and water-harvesting articles. Countries with lower GDP (Syria, Sudan) had more articles on water harvesting than on the more costly technologies, indicating that the nonconventional water resources research capacity and interest of a country may be influenced by its GDP.

Desalination research in Cyprus, Egypt, Israel, and Turkey is proceeding with involvement of the private sector. Research on reduction of energy consumption of a desalination plant with solar energy is a popular research topic in the region [28,31] and could contribute to cleaner future desalination. On the other hand, there were only two studies with quantitative information on the environmental aspects of desalination plants on the marine microbial community [39,41], while expansion of desalination continues unabated.

Irrigation with untreated or poorly treated wastewater will continue to increase as long as wastewater treatment does not keep pace with population growth and food demands [64]. Field experience and research has led Israel and Cyprus to the development of strict guidelines for wastewater reuse. However, laboratory analyses obtained with state-of-the-art chromatographic technologies are discovering an increasing number of compounds in treated wastewater, indicating that these guidelines may still be insufficient for a sustainable and safe use of the water [50,55,56]. More research on pollutant uptake by plants and long-term effects of wastewater irrigation on soil and groundwater is needed to prevent adverse effects on human health and the environment.

Motorized pumping and piped water supply have greatly reduced the scope of water-harvesting practices, which seem to occur nowadays mainly under conditions where water is very scarce or costly. Even though global studies indicate a potential increase in crop production as a result of water harvesting, no quantitative farmer-field crop and water-harvesting studies have been published recently in the region. Legal, financial, and environmental incentives are contributing to an increase in urban rainwater-harvesting systems worldwide [85], but these systems may provide only a small contribution to overcome water scarcity in our region [82] and suffer from water quality problems [81]. The ecological impacts of rainwater harvesting and the equity of water use have not been addressed by the researchers in the selected countries.

Consideration of socio-economic and climate change in the planning, design, and management of long-distance water transfer projects is becoming increasingly more important. Integrating financial, environmental, and resource costs in the price of transferred water, as required by the European Water Framework Directive, may be an option to improve the sustainability of this resource. As indicated by Tal [21] and Ghaffour [93], diversification of water resources with integral water resource management can provide a more secure and sustainable water supply in these water scarce countries. However, management of demand is equally important and should be a part of integrated water management strategies [12]. The limited extent and quality of the non-conventional water resources research in these water scarce countries indicate a lack of social capital. Nevertheless, as we can conclude from the reviewed articles, the Middle East is an interesting pilot case for non-conventional water resources research. Evolving trial and error processes in water resources management provide fruitful examples for our changing globe. There is, however, a need to improve the capacity of the academic sector in these countries to analyze and publish interesting case studies and findings and thereby, contribute to sustainable water use and governance.

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