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REVIEW

Climate Change and Water Scarcity: The Case of Saudi Arabia

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Abstract

BACKGROUND Climate change is expected to bring increases in average global temperatures (1.4°C–5.8°C [34.52°F–42.44°F] by 2100) and precipitation levels to varying degrees around the globe. The availability and quality of water will be severely affected, and public health threats from the lack of this valuable resource will be great unless water-scarce nations are able to adapt. Saudi Arabia provides a good example of how the climate and unsustainable human activity go hand in hand in creating stress on and depleting water resources, and an example for adaptation and mitigation.

METHOD A search of the English literature addressing climate change, water scarcity, human health, and related topics was conducted using online resources and databases accessed through the University at Albany, State University of New York library web page.

RESULTS Water scarcity, which encompasses both water availability and water quality, is an important indicator of health. Beyond drinking, water supply is intimately linked to food security, sanitation, and hygiene, which are primary contributors to the global burden of disease. Poor and disadvantaged populations are the ones who will suffer most from the negative effects of climate change on water supply and associated human health issues. Examples of adaptation and mitigation measures that can help reduce the strain on conventional water resources (surface waters and fossil aquifers or groundwater) include desalination, wastewater recycling and reuse, and outsourcing food items or "virtual water trade." These are strategies being used by Saudi Arabia, a country that is water poor primarily due to decades of irresponsible irrigation practices. The human and environmental health risks associated with these adaptation measures are examined. Finally, strategies to protect human health through international collaboration and the importance of these efforts are discussed.

CONCLUSION International, multidisciplinary cooperation and collaboration will be needed to promote global water security and to protect human health, particularly in low-income countries that do not have the resources necessary to adapt on their own.

KEY WORDS climate change, public health, Saudi Arabia, water reuse, water scarcity

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INTRODUCTION

It is expected that climate change will bring increases in average global temperatures (1.4°C–5.8°C [34.52°F–42.44°F] by 2100) and precipitation levels, but the magnitude and direction of these changes will vary regionally. These changes will significantly affect the quality and availability of water, as the hydrological cycle is intimately linked with climate change, and specifically with greenhouse gas in the earth's atmosphere associated with global warming. Some effects of climate change on the hydrological cycle will include variations in the quantity and seasonal distribution of precipitation, increased precipitation intensity,[1] increasingly frequent and severe temperature fluctuations and weather events,[2] redistributed balance between rain and snow, effects of sea-level rise on coastal communities, and increased evapotranspiration and reduced soil moisture.[1] These effects and irresponsible human activity threaten water security in many parts of the world, particularly in lower latitude, subtropical regions where total precipitation is decreasing, temperatures and evapotranspiration are rising, and potable water resources are being depleted. Water scarcity-related issues also directly jeopardize human health, as degraded water quality and poor sanitation increase risk for disease.[3]

The Middle East is now in a water crisis, with Saudi Arabia and the other countries of the Gulf Cooperation Council (GCC) already classified by the United Nations as water-scarce nations; only Oman sits slightly above the severe water scarcity threshold of 500 cubic meters per capita per year[4] (Fig. 1). Because water resources are already so scarce, the Middle East and North Africa regions will be particularly vulnerable to the effects of climate on water resources.[5] Saudi Arabia constitutes the majority of the Arabian Peninsula and is one of the largest arid countries without permanent rivers or lakes.[6] Located in the tropical and subtropical desert region of the Middle East between the Persian Gulf and the Red Sea,[6,7] temperatures can reach more than 50°C (122°F) in some areas, producing overwhelmingly hot and dry conditions. Long-term average rainfall across the country is 114 mm per year. Rainfall varies between 100 and 200 mm annually in the north, but falls below 100 mm per year further south. Some small areas at greater elevations in the west and southern parts of the Kingdom, however, do see up to 500 mm of rainfall annually.[6] Despite being one of the wealthiest nations globally due to swift economic growth and prosperity from oil,[8] Saudi Arabia is one of the poorest nations in terms of natural renewable water resources.[9]

Mismanagement of water use in the agricultural sector and an increasingly Westernized and consumerism-based shift in lifestyle are mostly to blame for Saudi Arabia's water-starved status, as precious groundwater sources have been injudiciously used over many years to the point of depletion.[10] Furthermore, the combination of a greater-than-average annual population growth rate (2.5%) coupled with an 8.8% annual increase in the demand for water and the changes brought about by climate change[9] will have significant effects on the future of both the availability and quality of water resources in Saudi Arabia.[5] Saudi Arabia has become a global leader in both the development and use of desalination technologies, which now have replaced groundwater as the primary source of drinking water in the Kingdom.[11]

The ability to adapt to a changing climate is largely dependent on national resources and thus the hardships associated with climate change are not equally distributed, with poor and disadvantaged populations and countries suffering most.[2,5] Compared with other countries in the Middle East, Saudi Arabia is fortunate to possess the ability to make notable progress in addressing the growing water demand because of its economic stability and wealth. For example, whereas Saudi Arabia constructed desalination plants as early as the 1970s, other poorer countries like Syria and Yemen do not have the means to finance, operate, and maintain expensive desalination plants, although their need for water resources are most urgent.[10] Saudi

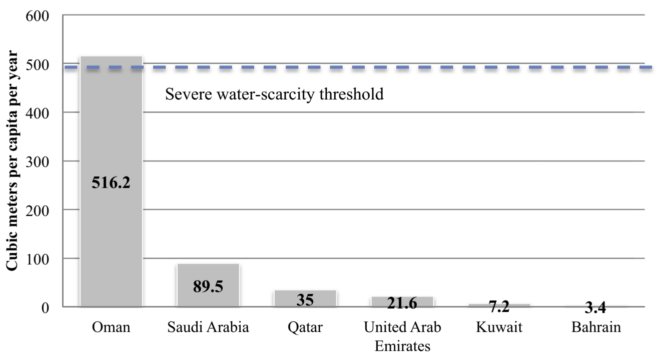

Figure 1. Renewable water resources in the Gulf Cooperation Council (GCC; 2009). Adapted from reference[4].

Arabia can also afford to outsource food crops to reduce domestic production and water use,[12] and also has been investing in wastewater reuse to curb water demands.[13] Despite these advantages, Saudi Arabia too will continue to face challenges in adapting to climate change and dwindling water resources, and evidence from the literature suggests that the adaptation methods being pursued may not be sustainable and may even exacerbate climate change and water scarcity in other parts of the globe.[14,15]

Saudi Arabia provides an illustrative example for climate change and water-scarcity issues for many reasons. First, it is an example of how the climate and unsustainable human activity go hand in hand in creating stress on and depleting water resources. Second, as both a water-scarce and a very wealthy nation, Saudi Arabia also serves as a leading example for adaptation and mitigation, which can be very costly. Finally, recent reports demonstrate that Saudi Arabia is beginning to convert many conventional energy sources to renewable and more sustainable ones (ie, solar),[16,17] setting yet another example for other nations that will more likely than not embark on their own adaptation and mitigation efforts. However, because low-income countries will suffer most from the consequences of climate change and water scarcity, we argue the need for alternative, sustainable, environmentally friendly, and *affordable* technologies to be developed, and discuss the importance of international collaborative efforts to protect human health across the globe, particularly the health of disadvantaged low-income populations. This is crucial as human health is intimately linked to the availability and quality of water resources, as further explored here.

METHOD

This review was informed by existing literature obtained through Internet resources. Peer-reviewed, English-language articles were collected using Google Scholar and the University at Albany State University of New York library system, which provides access to databases such as ACM Digital Library, EBSCO: Academic Search Complete, Lexis Nexis, Science Direct, JSTOR, Worldcat, Web of Science, Medline, and PubMed. Keywords used in these literature searches included *Saudi Arabia and water*; *Saudi Arabia and water scarcity*; *climate change and water scarcity*; *water scarcity and public health*; *water scarcity and sanitation*; *climate change and public health*; *wastewater and Saudi Arabia*; *wastewater reuse and Saudi Arabia*; *virtual water*; *desalination*; and *desalination and Saudi Arabia*. We tried to limit literature addressing water use, water scarcity, and the status of water resources in Saudi Arabia primarily to articles published within the past 5 to 7 years so that the information referenced was not outdated. Government and sponsored web pages and PDF documents containing information on these topics also were used.

RESULTS

Climate Change, Water Scarcity, and Human Health. Water scarcity is not only an issue of water availability, but also of the quality of available water. Climate change will contribute to water scarcity not only through increased temperatures and prolonged drought periods that put strain on water demand and existing water resources, but also through the degradation of water resources through extreme precipitation events that carry pathogens and other contaminants into waterways via runoff and flooding.[1] Water quality thus becomes a matter of sanitation, as contaminated water in the environment poses significant health risks.[18] Estimates from the World Health Organization indicate that 1.1 billion people worldwide are without access to safe potable water, and 2.4 billion people do not have access to adequate sanitation.[3] Approximately 900 million people suffer from diarrhea worldwide each year from exposure to or consumption of contaminated water.[3] For example, campylobacteriosis, which causes abdominal pain, diarrhea, headache, fever, and nausea, is caused by exposure to *Campylobacter* sporidium (sp.) in contaminated drinking or recreational water. Outbreaks of this illness often result from heavy rain events, particularly when preceded by drought, when rainwater runoff transports pathogens and other contaminants (ie, sewage overflow, manure, fecal shedding) into water systems.[19]

There is evidence that increasing water temperatures due to global warming promotes disease by creating conditions that are advantageous to some (but not all) water-borne pathogens, enhancing parasite metabolism, increasing the number of transmission stages and fitness of the pathogens, and lengthening the natural transmission season.[20] *Vibrio*, *Cryptosporidium*, and noroviruses are the other most common agents responsible for gastroenteritis worldwide, and like *Cambylobacter* sp., the persistence, size, and infectivity of these pathogens are all responsive to climate.[19] Malaria, filarasis, and bilharziasis are other diseases related to water and sanitation.[3]

Unsurprisingly, climate and water scarcity issues also affect food sources, as low availability of water has a direct negative effect on food production, and heavy precipitation and increased flooding from rain and sea-level rise means a greater likelihood of food contamination and disease.[3] Sea-level rise is another consequence of climate change that will affect water resources, and coastal communities are already suffering impacts from sea-level rise with seawater intrusion salinizing thousands of wells.[5]

Poor and developing countries will be affected most by climate change and water-related health issues, and are also the most economically disadvantaged for adaptation and mitigation. Many of these countries do not have formal water utilities or adequate infrastructure to begin with. Because of this, it is anticipated that many of these communities will turn to unsustainable adaptation practices, continuing to overexploit groundwater or increase the reuse of untreated wastewater.[3] Water scarcity, poor sanitation, and poor hygiene collectively pose substantial health risks, particularly in low-income countries, significantly contributing to the global burden of disease.[21] Children living in low-income countries are especially vulnerable, and morbidity and mortality in children due to diarrhea is high.[3] Of the 1.8 million children who die each year from diarrheal diseases worldwide, 90% are children in developing countries under the age of 5 years. Reports from the Disease Control Priority Project estimate that 90% of these deaths can be avoided with improved sanitation (ie, isolating fecal matter from the environment), hygiene (ie, handwashing with soap), and water supply.[21]

There is also the potential for conflict to arise at the local level in the coming decades as resources are depleted, creating competition for water resources, unless cooperative policies are included in adaptation measures.[3]

The Case of Saudi Arabia. ***Sources of water in Saudi Arabia.*** Water demands in the Kingdom are satisfied through renewable groundwater and surface water sources, nonrenewable groundwater sources, desalinated seawater, and treated wastewater.[22] With no permanent lakes or rivers and very little rainfall, surface and renewable groundwater is extremely limited. In the event of rainfall, surface water created by flash flooding (roughly 16 million cubic feet of runoff each year) is captured in more than 200 dams across the Kingdom and is stored in reservoirs.[23] Approximately 2045 million cubic meters of surface water comes from rainfall each year, primarily in the west and southwest regions of the Kingdom.[24]

In 1980, 60% of the 10 billion cubic meters of water used in Saudi Arabia was derived from surface water and other renewable resources (shallow aquifer recharge). By 2010, water consumption increased by 75% (17.5 billion cubic meters), although the supply of renewable water resources remained constant. With this limited supply, only 34% of water consumed in 2010 came from renewable sources, whereas the use of nonrenewable groundwater increased significantly (from 38% to 59%) to cope with the increased demand.[4] Still, the rate at which renewable groundwater resources (ie, shallow aquifers) are recharged does not stand up to how quickly they are being depleted; it has been estimated that at the current rate of withdrawal, these water supplies will be gone in less than 50 years.[13] FAO-Aquastat data from 2010–2012, presented in Figure 2, illustrates how limited these water resources are in Saudi Arabia compared with global averages.[25]

One study[26] that examined the effects of climate change on water resources in Saudi Arabia estimated that rainfall in the northern part of the country will decrease by an average of 10 mm per year, exacerbating the existing drought conditions. Alternatively, precipitation in the areas covering in the central and southern regions is expected to increase by 15 to 25 mm per year and by 109.7 to 130.4 mm per year, respectively, by 2050.[26] Despite increased rainfall in some areas, evapotranspiration is also expected to increase during this same time, and less than half of the water lost to evapotranspiration will be replenished by rainfall, leaving surface water resources still limited.[26] Furthermore, rain events

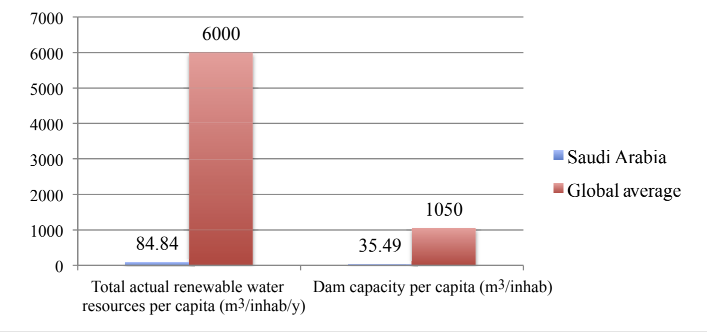

Figure 2. Comparison of average global water resources with water resources in Saudi Arabia. Data adapted from FAO-Aquastat, based on 2010–2012 data.[25]

will be short and severe, causing flash floods and runoff that can carry contaminants into existing reservoirs of water, jeopardizing the quality of existing water resources.[1]

The 2 main sources of nonrenewable groundwater are the Kingdom's sedimentary and deep rock aquifers, which hold "fossil" water that was formed approximately 1000 to 32,000 years ago.[22] Globally, paleohydrological evidence suggests that groundwater recharge took place before and sometimes during the Late Pleistocene glaciation, or during the Early Helocene period, when climates were at least 5°C cooler and wetter. Today, these fossil aquifers are considered "storage dominated rather than recharge-flux dominated" as only a very tiny fraction of total groundwater storage is due to recharge.[27] In general, pumping more water than can be replaced by natural recharge rates is to blame for low groundwater levels, not climate change-induced reductions in recharge rates, although climate changes do affect groundwater flow into shallow aquifers.[28] With 8 principle aquifers and 9 secondary aquifers in Saudi Arabia, groundwater withdrawal once supplied the majority (90%) of water used in the Kingdom and was the primary source of potable water.[6,22]

Another study[27] suggested "managed aquifer recharge" as a potential strategy to combat the strain that climate change will put on water resources, using depleted aquifers to store any excess surface water, desalinated water, and treated wastewater to be used during extreme droughts. Another group of researchers[29] echoed this recommendation, and highlighted the need for the construction of more dams to capture storm water for storage, especially in anticipation of climate change.

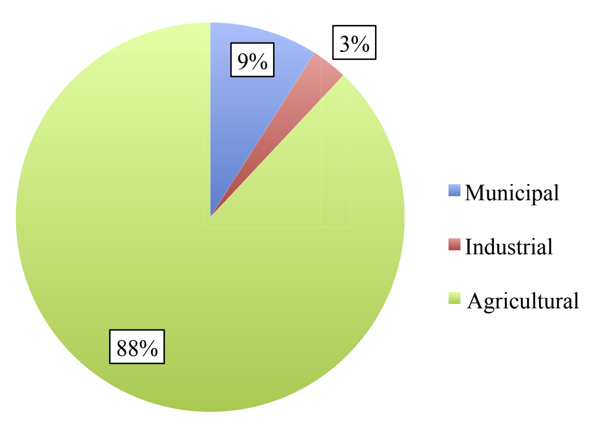

Figure 3. **Sectoral withdrawals (%).** Data adapted from FAO-Aquastat (2006).[25]

Water use in Saudi Arabia. Liberal water use and careless water supply management coupled with unchecked population growth, irresponsible agricultural policies, and years of war have led to an unsustainable culture of water usage in Saudi Arabia.[10] For example, although the renewable water sources in Saudi Arabia are very limited, the country is third only to the United States and Canada in the amount of water used per capita, with a level of consumption around 250 L per capita daily.[13] The low tariff structure for water (US$0.03/cubic meter) has provided little to no incentive for Saudis to conserve water.[13] Saudi Arabia consumes nearly 7 billion cubic meters of water daily,[9] the result of a severe lack of government supervision in the water sector.[13]

According to the annual report of the Saudi Arabian Monetary Agency, more than 80% of total water demands fall on the consumption practices in the agricultural sector[9,26] (see Fig. 3), which uses a large proportion of nonrenewable groundwater.[13]

Water-liberal irrigation practices have contributed largely to this issue, as 35% of farmland is irrigated using traditional methods of flood irrigation, which uses more water than modern practices like drip irrigation or using sprinkler systems,[13] and since the late 1970s, landowners had been allowed to freely extract water from aquifers without limitation to maintain irrigated fields in the desert.[12] This led to an average of 5 trillion gallons being pumped annually by the 1990s, enough water to drain Lake Erie in only 25 years.[12] Reducing the production of the most water-intensive crops, such as wheat, is an important strategy to adopt, and the Saudi government intends to end domestic wheat production by 2016.[13] The government also has plans to transition to greenhouses for producing fruits and vegetables, and has banned growing other water-intensive crops like alfalfa, which was used primarily for animal fodder.[10]

Adaptation and Mitigation Practices in Saudi Arabia.

In 2011, the Saudi Agricultural and Livestock Investment Co. (SALIC) was established to secure stable food supplies in order to avoid food shortages, with the equivalent of US$800 million to work with.[30] SALIC has made investments in the Canadian Wheat Board, which means a portion of its grain will be sent to Saudi Arabia. In addition to Canada, Australia and Brazil are also considered "priority destinations" for investments in various grains and red meat.[30] Plans have been made by the Saudi government to rely almost entirely on imported crops from other countries to feed its population of 30 million people.[12] Arrangements are also underway for outsourcing food production to countries such as Sudan and Ukraine and others in South America and Asia, where Saudi Arabia will grow its own food to be exported back to the Kingdom.[31] This will significantly reduce the demand for water from the agricultural sector.

The trouble with outsourcing. Despite local benefits of outsourcing food resources, this action puts pressure on other food markets and water resources, as importing water-intensive foods from other countries is in essence importing what has been termed *virtual water*,[5] meaning the amount of water that was used to grow the food being exported.[32] In 2014, the agricultural imports of Saudi Arabia (and China) from the United States were at an all-time high, and in effect these countries are really importing US water supplies in the form of food.[5]

The argument in support of virtual water trade is that it promotes "global water use efficiency" and "distribution of scarcity," with water-rich nations exporting to water-poor nations, which constitutes a "net water gain" for the latter nations.[33] However, it has been demonstrated[33] that this argument assumes that all water-rich countries are economically advantaged in terms of "producing foodgrains as compared to the arid and semi-arid countries; and that the comparative advantage essentially comes from more favorable climatic conditions that reduce evapotranspiration, and availability of water as the 'free good' in the form of soil moisture that reduces the irrigation water requirements" (p. 760). This is often not true, and in fact, many of the water-rich countries still heavily rely on imports from other countries, whereas many countries that are water-starved or are approaching the point of water stress still export foodgrains, livestock, and poultry. Therefore, within the real-world context of global virtual trade, the concepts of "global water-use efficiency" and distribution of scarcity are not truly realized.[33]

These practices put us at risk for "a global domino effect" where one country's water resources run low, so it turns to another, creating extra burden on those water reserves.[12] For example, a large Saudi dairy producer, Almarai, owns 15 sq mi of desert farmland in Arizona, which is used to grow alfalfa to be exported back to the Kingdom. Requiring almost quadruple the amount of water as wheat, these crops are being watered from reservoirs supplied by the Colorado River, which are at record lows, putting the supply of drinking water for Las Vegas, San Diego, and Los Angeles in jeopardy.[12]

Desalination. Saudi Arabia is the largest producer of desalinated water globally.[14] The Kingdom houses the Marafiq complex in Jubail, which is considered "the world's largest independent water and power project"[7] (p. 28) as desalination technology now supplies 60% of water demand in the Kingdom[11] and produces more than 70% of the Kingdom's drinking water and 5% of its electricity supply.[24] The desalination process requires a significant amount of capital and energy, and major transmission lines are needed for transporting desalinated water from plants to cities that are several hundred kilometers away.[13]

Fueled by oil, it has been estimated that about half of domestic oil production in the Kingdom is now used for desalination.[7,13] The increasing demand for water, presently near a 9% annual growth rate and estimated to double by 2035, could have serious implications for the Saudi economy as it will likewise increase domestic oil consumption.[9] The Saudi Water Conservation Council plans to increase production of desalinated water from 1.2 billion cubic meters to 1.825 billion cubic meters by the end of 2015.[9] The deputy electricity minister recently stated that Saudi Arabia will need to spend US$213.3 billion over the next decade to meet the demand for water and electricity, which is rising annually by roughly 8%. The affluent lifestyle of an increasingly wealthy population is responsible for this growth in demand.[34] Furthermore, superfluous water consumption is encouraged by a low tariff of only US$0.027 per cubic meter,[7] which is also responsible for the enormous costs that fall upon the public treasury to produce water, which costs roughly US$3.20 per cubic meter.[9] Increasing domestic oil consumption to meet increasing water and energy demands puts the Kingdom at risk for losing its place as one of the leading global providers of oil, and could affect its social and financial stability.[35]

Despite the human health benefits of seawater desalination, the chemical discharges and byproducts that may negatively affect coastal waters and the health of marine life are of great concern.[14] The brine that is discharged from the desalination plants is highly concentrated and increases ocean salinity—another threat to surrounding ecosystems.[15] Sea life such as jellyfish, plankton, and algae and other suspended solids can be sucked into the desalination plant through intake pumps.[36] The tremendous amount of energy needed to carry out the desalination processes is also responsible for air pollutant emissions,[14] which could exacerbate climate change, especially as more desalination plants are developed in the future.[15]

There has been a call for the evaluation of these environmental effects and the creation of safeguards to help mitigate the adverse effects and to promote sustainable use of desalination technology.[14] Saudi Arabia recently announced intentions of weaning the Kingdom off diesel energy and has been making great strides in solar development, and has plans to build the world's first full-size solar-powered desalination plant.[37] Although this will still pose threats to surrounding marine environments, it is a step in the right direction. Another alternative technology that has been developed[38] is an "integrated solar-driven desalination system" that is portable, and produces potable water using a membrane distillation process. Using a self-contained system and relying on solar energy, the system was designed so that those living in remote, arid areas of the Kingdom with limited resources for potable water and electricity will be able to operate it independently. Studies of this system are being conducted by King Saud University, but small-scale tests have shown promising results.[38] Unfortunately, the inability of such systems to guarantee adequate supply of water to the entire country means that large desalination plants are going nowhere soon,[35] and despite the current progress in solar development being made in Saudi Arabia, the existing desalination plants will continue to run on conventional power sources.

Although the human health benefits of desalination cannot be denied, it is critical to develop alternative strategies for maintaining adequate water resources, or to modify this technology to reduce its harm on the environment. Climate change is a global issue, and therefore the global effect of local adaptation measures must be considered. Saudi Arabia is the global leader in desalination technology, but many other countries (eg, Australia, Spain, the United Kingdom, the United States, India, China, Algeria, Egypt, Israel, Jordan, Libya, Tunisia) have been following suit.[5,15] Increasing energy-intensive desalination infrastructure will continue to negatively affect surrounding water ecosystems and contribute to greenhouse gas emissions, aggravating climate change and exacerbating the global effects that they are combating in the first place.

Water recycling and reuse. Water recycling is gaining favor as an efficient way to curb demands on water resources, and to help balance both water and food security,[39] and it can be used to generate water for many nondrinking purposes, such as agriculture, environmental uses, horticulture, and maintaining green spaces.[40] The constancy, reliability, and reduction of demand on the environment are other advantages of properly managed water reuse. It also reduces the amount of both treated and nontreated effluent into the environment, depositing organic and inorganic nutrients (eg, nitrogen and phosphate) into water systems, which can cause eutrophication and algal blooms and severely degrade existing bodies of water.[41]

Water reuse and recycling also is a positive step toward climate change adaptation and mitigation for many reasons. When used in agriculture, it saves energy and reduces the cost of freshwater pumping, providing irrigation and reducing the water footprint of food production. It also can provide adequate nutrients and fertilizer for crops so that mining for mineral fertilizers may be decreased, reducing the carbon footprint as well. For example, it has been demonstrated that reusing treated municipal wastewater for agricultural irrigation in Saudi Arabia indeed provided adequate nutrients, lowered costs for irrigation and fertilization, and increased yield and profit for wheat and alfalfa.[42] The collection and treatment of wastewater for reuse also reduces the introduction of pollutants into waterways.[43] Some say that using recycled water for irrigation improves soil health,[43] however, the salinity of recycled water is of concern as higher levels of sodium can cause soil issues such as low macroporisity, low water storage, poor infiltration and aeration, reduced organic carbon, nutrient imbalances, and low biological activity, which harms soil health and reduces crop yields.[41]

Presently, Saudi Arabia uses less than 20% of the 672 million cubic meters of wastewater collected and treated each day. However, with the establishment of the National Water Company in Saudi Arabia, the Kingdom is anticipated to become the third largest market for water reuse globally (after the United States and China),[44] with plans to provide 100% of the water supply to all cities with a populace of more than 5000 people by 2025[13] and to invest US$23 billion into sewage collection and treatment infrastructure.[44] This is a necessary expense because recycled wastewater contains high volumes of microbial contaminants (pathogens and fecal indicators), viruses, protozoa, helminths (intestinal nematodes and tapeworms), trace organics and heavy metals, endocrine-disrupting chemicals, and pharmaceutically active compounds (ie, antibiotic residues) and therefore requires thorough treatment prior to reuse.[40,41,43,45] Cholera and typhoid fever are examples of communicable diseases that can be transmitted by eating raw vegetables irrigated with poorly treated or untreated wastewater.[43] It is estimated that 10% of the world's population consumes crops irrigated with poorly treated or untreated wastewater.[28]

Still considered a developing country, there is low confidence from the general public in the ability of Saudi Arabia's wastewater treatment processes to adequately remove these contaminants. Thus, there remains reluctance to reuse more of the treated wastewater out of concern for public safety.[39] The use of inadequately treated wastewater for irrigation directly exposes agricultural workers to microbial contaminants, and indirectly exposes consumers who eat contaminated produce. Studies monitoring the effectiveness of treatment processes at a wastewater treatment plant in Saudi Arabia have found that the current processes attained the quality requirements for restricted irrigation (limited to fodder and industrial crops, cereals, trees, and pastures[21]) but not for unrestricted irrigation (vegetables that may be eaten uncooked[21]),[39,46] and only if the treated effluent was also chlorinated.[39] Chlorinated effluent had roughly 1.8×10^2 most probable number/100 mL of fecal coliforms in the finished product. Current levels of coliforms in wastewater permitted for reuse is <1000 colony-forming units (CFU)/100 mL and <2.2 CFU/100 mL for restricted and unrestricted irrigation, respectively.[39]

Wastewater treatment requirements lack guidelines for antibiotic residues.[39,45] This is problematic because antibiotic residues in reclaimed water can create a microbial environment in which antibiotic resistance is spread through selection of antibiotic-resistant genes, which can then be passed from one bacterium to another.[45] The result is a *perfect microbial storm* defined as "a phenomenon where novel microbial threats emerge with elevated frequency that can create an environment that allows infectious diseases to emerge and become rooted in society" (p. 370).[45] Animals and humans are susceptible to illness outbreaks and the transference of antibiotic resistance on consumption of raw produce contaminated by microbial pathogens or antibiotic-resistant bacteria.[47] Results from one study demonstrated that 76.5% of the bacterial populations found on produce purchased from various food markets and vendors around Taif City in Saudi Arabia were resistant to at least one antibiotic.[47] Chemical treatment, bioadsorption followed by physical separation, and nano- or reverse osmosis membrane filtration after conventional treatment are effective forms of antibiotic removal.[45]

Expanding wastewater recycling in Saudi Arabia is a promising strategy for alleviating pressures of water demand, but it will be absolutely imperative to incorporate antimicrobial resistance into risk assessment and reuse planning to minimize health risks to farmers and consumers.[39]

Rainwater harvesting. As previously noted, climate change will have variable regional effects on rainfall over time, with some areas of the globe experiencing reduced rainfall and more drought, whereas others will experience more frequent heavy rain events. One study examined trends in the yearly rainfall and aridity in Saudi cities and showed an even split in the number of cities that will see reduced annual and maximum rainfall and those in which the annual and maximum rainfall will increase.[48] The remaining cities studied show increasing maximum rainfall, but decreasing annual rainfall indicating more extreme rainfall events that produce flooding. Therefore, rainwater harvesting (RWH) could be a practical solution to help mitigate water shortage, especially in remote areas.[48] RWH technology and practices have been around for thousands of years, and allow for storing rainwater from land surfaces, rooftops, or rock catchments into natural or artificial reservoirs.[49] Developing a system for RWH may be a viable option for Saudi Arabia; the largest quantity of runoff (about 60%) from rainfall occurs in the southwestern region of the Kingdom and this could be collected, stored, and transported to other parts of the country through new and existing pipelines.[22]

An important consideration will also be the quality of the harvested rainwater. Depending on the atmospheric conditions, rainwater may be contaminated with pollutant particles, microorganisms, heavy metals, and organic substances. The quality of rainwater also depends on what catchment area it collects from as the catchment areas themselves may be sources of heavy metals and organic substances. For example, roadways may have such pollutants originating from brakes and tires, polycyclic aromatic hydrocarbons from incomplete combustion processes, or bacteria, viruses, and protozoa from fecal pollution by animals. It is important to treat and disinfect harvested rainwater, which can be done inexpensively through chlorination, slow sand filtration, or pasteurization by solar technology.[49]

In other countries that already use RWH, these systems demand great involvement from citizens who own and manage the collection and sanitation systems involved. In this way, RWH is a decentralized supply of water and reduces governmental control over the flow of water.[50] Allowing citizens to be responsible for water collection could increase awareness around consumption habits and lead to greater water conservation, however, with human health risks similar to those associated with waste water recycling and reuse, water quality and sanitation would be critical issues to address in RWH and use as well.

Protecting Human Health. One of the critical issues regarding public health is the fact that the effects of climate change and water scarcity disproportionately affect poor communities and poorer members of society, and yet they do not have equitable means to adapt to these problems.[2,5,18] Therefore, it is important to approach human health and climate change issues as global public health issues.

The 2015 Lancet Commission on Health and Climate Change, a multidisciplinary, international collaboration between Europe and China, has outlined recommendations for policy responses to climate change to ensure global human health, including the health of poor nations with limited resources.[51]

The commission emphasizes the need for global cooperative efforts in tackling climate change stating, “Reducing inequities within and between countries is crucial to promoting climate change resilience and improving global health” (p. 2). This public health perspective approach to the issue also should be accompanied by sustainable development that will provide access to clean and safe water, air, and food, health care accessibility, and declines in economic and social inequities.[51] Some of the recommendations promoted by the commission to accomplish these goals involve international collaborations to create policies and frameworks for cutting out coal and reducing carbon emissions and supporting one another in these efforts, expanding renewable energies in low-income countries, and conducting research in climate change and public health at local and national levels through monitoring and surveillance to gain understanding of adaptation needs, promote healthier lifestyles for individuals and the planet, particularly in cities (eg, energy-efficient buildings, increased access to green spaces, low-cost public transportation), and to quantify improvements in public health systems due to adaptation and mitigation measures (ie, reduced health care costs, enhanced economic productivity, avoided burden of disease).[51]

It is also extremely important for any collaborative intervention strategies to make improved access to safe water and sanitation priorities because these issues contribute most greatly to the burden of disease.[52] Typically, high-income countries have roughly 98% access to improved drinking water and improved sanitation[52]; for example, access to improved water and improved sanitation in Saudi Arabia presently sits at 93% and 100%, respectively.[53] In low- and middle-income countries, coverage of improved water and improved sanitation is estimated at 79% and 49%, respectively.[52] It has been argued that the 4 universal barriers to progress in water access and sanitation are[52]:

1. Inadequate investment in water and sanitation infrastructures;
2. Lack of political will to tackle the tough problems in this area;
3. Tendency to avoid new technological or implementation approaches and apply conventional water and sanitation interventions, without community involvement, repeatedly, even when they are inappropriate for the specific environment and community needs; and
4. Failure to conduct evaluations of water and sanitation interventions to determine whether they are successful and sustainable (p. 52).

This argument does not acknowledge that poor and disadvantaged countries and governments may lack the resources necessary to make investments in infrastructure, technology, or conduct evaluations, but also highlights the need for international cooperation and collaboration particularly to help lower-income countries overcome these barriers. As these issues are strongly tied to climate change, adapting to and taking robust action to mitigate present health effects is important for empowering the populations most at risk and reducing the underlying vulnerability in order build a foundation for longer-term development. The goal is to give all nations an equitable and reasonable chance to respond to the worsening effects of climate change with resiliency, and limit the negative health effects and burden of climate change.[51]

DISCUSSION

Saudi Arabia serves as an illustrative example of how poor water management can have severe consequences for the water sector, especially as climate change puts a strain on the availability and quality of water resources. However, Saudi Arabia also serves as an example for water-scarcity management. By developing desalination plants, expanding water recycling processes and infrastructure, transitioning from domestic agriculture to outsourcing food products, and now taking the reins on solar development and beginning to phase out fossil fuels, Saudi Arabia is doing just about everything it can to ensure domestic water resources will be available and accessible, and that it will be able to sustain these practices. But the potential and real global effects of these adaptation and mitigation practices must be considered.

Saudi Arabia is fortunate to have the financial and economic resources to respond to its water crisis, but other countries in more dire circumstances do not have that luxury, and should not bear any extra burden from adaptation practices of other countries that may exacerbate climate change and water-scarcity issues. The strain on global water resources through mismanaged virtual water trade could prove problematic if not properly monitored, and efforts should be made to actually incorporate the concepts of “global water-use efficiency” and “distribution of scarcity” into global water trade. Desalination technologies, although progressing in a slightly more sustainable direction (solar), still will pose significant threats to surrounding marine life and ecosystems. Furthermore, while the nonsolar desalination plants are still in action, the continued emissions of pollutants into the atmosphere could exacerbate climate change, which could make the upcoming challenges of climate change all the more formidable, and adaptation and mitigation much more difficult and costly. We were unable to find any mention of anticipated effects, if any, of sea-level rise on desalination utilities, but do wonder whether or not coastal flooding could disrupt desalination activities. The potential for rising sea levels to jeopardize current and future desalination processes might be an important issue to investigate and anticipate in countries adopting this technology.

There is clearly a strong need for the development and expansion of other alternative adaptation methods that are not only sustainable and environmentally friendly, but also affordable. Rainwater harvesting and smaller, portable, solar-driven desalination systems would be beneficial at local levels, and provide a means for communities with less governmental involvement to have some control over their own water resources. The trouble with these strategies is that they can still put public health at risk, for example, if the desalination systems are not properly used and maintained, or if harvested rainwater is not properly treated and thus exposes users to the contaminants previously discussed.

The goals of the 2015 Lancet Commission very clearly intend for all nations to cooperate and collaborate in reducing global inequities among countries in their ability to adapt to climate change and maintain public health. More importantly, it has been pointed out that part of the novelty of the Lancet Commission is that it intends to tackle threats to health from climate change using an international multidisciplinary approach, calling on “climate, social, political and environmental scientists, geographers, experts in biodiversity and energy policy, engineers, economists, and, of course, health professionals”[54] (p. 1). Climate change is an exceedingly complex issue that involves myriad disciplines, and thus the need for expertise from all these fields and more to better predict and plan for the consequences of climate change is paramount.

CONCLUSION

Protecting human health in the face of climate change and water scarcity will be largely dependent on the resources available to communities to conserve and provide access to safe drinking water and adequate sanitation. However, global resilience cannot be achieved if communities and countries develop strategies in isolation. Climate change is a global issue, and thus successfully adapting to the consequences of climate change, including increasing water scarcity, will depend on cooperative and multidisciplinary international efforts.

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