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Teaching and Educational Methods

Teaching Water Economics in a Desert Environment

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Abstract
Teaching water economics in a desert environment is less complex than in other environments. Economic methods dealing with the interaction between surface and groundwater, surface water pollution, water for nature, and hydropower are not in need in desert environments. The course focuses on demand-side policies such as quantity restriction, rate setting, technology adoption, and comparisons of policies oriented toward reducing water demand and addressing the wasteful use of water. Often adopting water-saving technologies have the ability to reduce demand without decreasing users' utility. We discuss the right of access to water and fairness. The course addresses the rationale for supply-side policies implemented in Gulf Cooperation Council (GCC) countries. We emphasize the environmental impacts and energy requirements of desalination as limits. Alternative sources of water for cities, such as the expansion of existing agricultural water markets to encompass trade between farmers and cities is explored. The course looks into the social impediments of treated wastewater recycling in farming. The course is taught since 2011 to undergraduate students in the form of lectures and lab work with the support of videos and flipped classroom. During the last weeks of the course, each student presents to the class a paper on the main issues addressed.

1 Introduction

Teaching water economics in a desert environment is less complex than in other environments. Rivers and surface water are absent in desert environments. Hence, all issues related to the interaction between surface and groundwater, surface water pollution, water for nature, and water for hydropower are irrelevant. Economic methods dealing with the above issues are not needed. Conventional renewable freshwater is in the form of groundwater found in relatively limited volumes spatially dispersed. Supply of urban water depends mainly on desalination, the nonconventional resource.

Traditionally in desert environments, the main source of water is groundwater. Life was organized around the springs, then horizontal wells called Qanats and Aflaj were developed hundreds of years before Christ (Jomehpour, 2009), and water flew by gravity from the aquifers to the oasis. There was no need of energy to abstract the water from the aquifers. However, the initial investment cost of drilling the horizontal wells was high enough and, in many circumstances, costed several human lives due to accidents from tunnel collapses on the workers (MRMWR, 2008). Water was scarce, and its management was of upmost importance. Water institutions were developed, and both common and private ownership was established. Access to water for basic human needs and for animals for local people and nonlocals was clearly established. Water distribution among economic sectors, priority of use, recycling, use of chemicals, and balancing of supply and demand within seasons and inter-annually were closely monitored (Zekri & Al-Marshudi, 2008). The event of the modern states in the 1970s, driven by the exploitation of hydrocarbons, led to a deep transformation of the economy and the water sector. Abundant and cheap energy led to the construction of tens of desalination plants in the Gulf Cooperation Council (GCC) countries to secure water for the booming economies (Reddy & Ghaffour, 2007). Water seemed unlimited, and supply was encouraged by a high demand. The increase in demand is due to the very low prices administered, population growth, immigration, concentration of populations in cities, and high income of the local citizens as well as by the stable profits desalination plants generate for private investors (Williams, 2022). The consequence is an erosion of the water management knowledge and culture accumulated over centuries. Urban areas became independent of the limited, if any, renewable sources of water and depended almost totally on desalination. Four out of six GCC countries, Bahrain, Kuwait, Qatar, and United Arab Emirates (UAE) have less than 20 m^3/cap/year of renewable water resources (Figure 1).

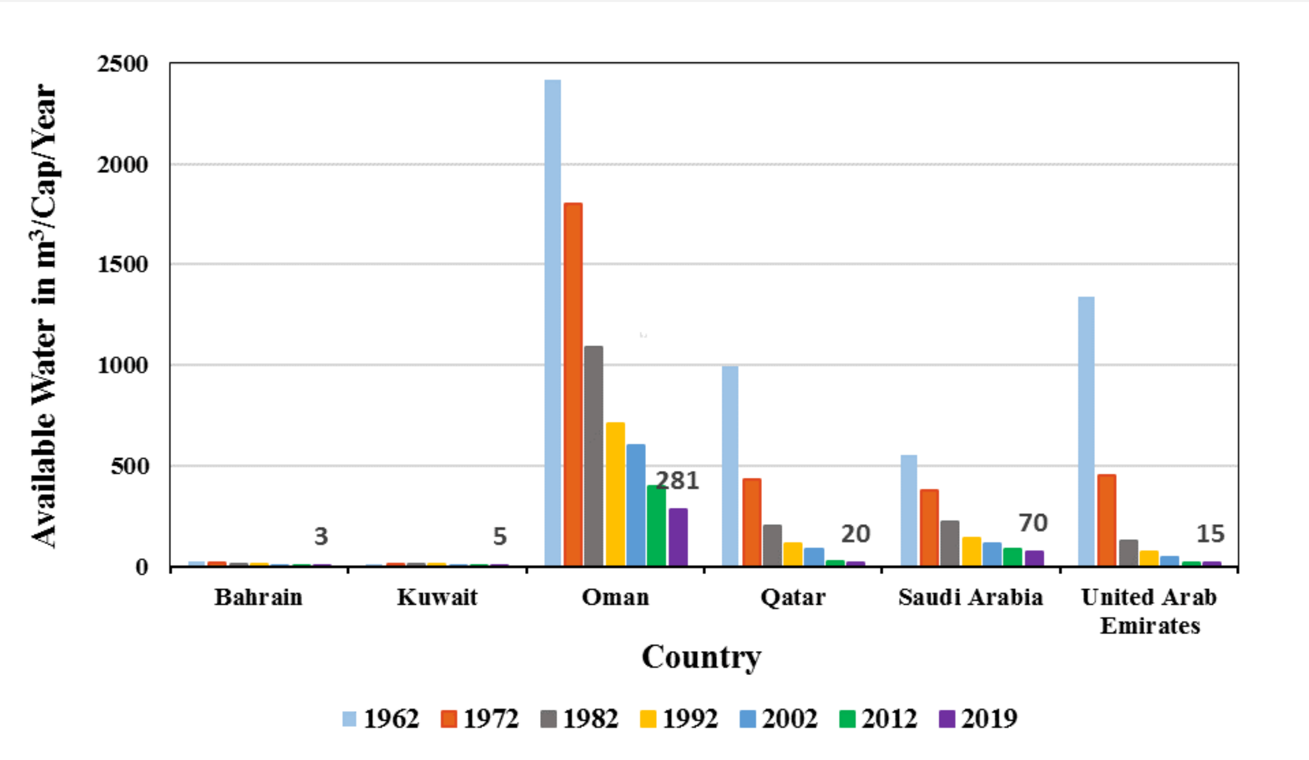

Figure 1. Available Renewable Water Resources for Gulf Cooperation Council Countries in m3/Cap/Year 1962–2019

Source: Based on World Bank data. https://data.worldbank.org/indicator

Although it is difficult to associate an exclusive desert climate to a whole country, such as the case of GCC countries, several other countries have large areas of inhabited hot deserts with no surface water. Figure 2 shows a map of countries with hot desert climate (BWh) and cold desert (BWk). A non-exhaustive list of these countries includes Algeria, Angola, Australia, Botswana, Djibouti, Chad, Egypt, Eritrea, Ethiopia, India, Iran, Iraq, Kenya, Libya, Mali, Mauritania, Mexico, Morocco, Namibia, Niger, Pakistan, Tunisia, Senegal, Sudan, South Africa, Syria, and United States (Las Vegas). Most of the countries with hot desert climate have parts of their territory under water stress and can benefit from this paper to develop similar courses.

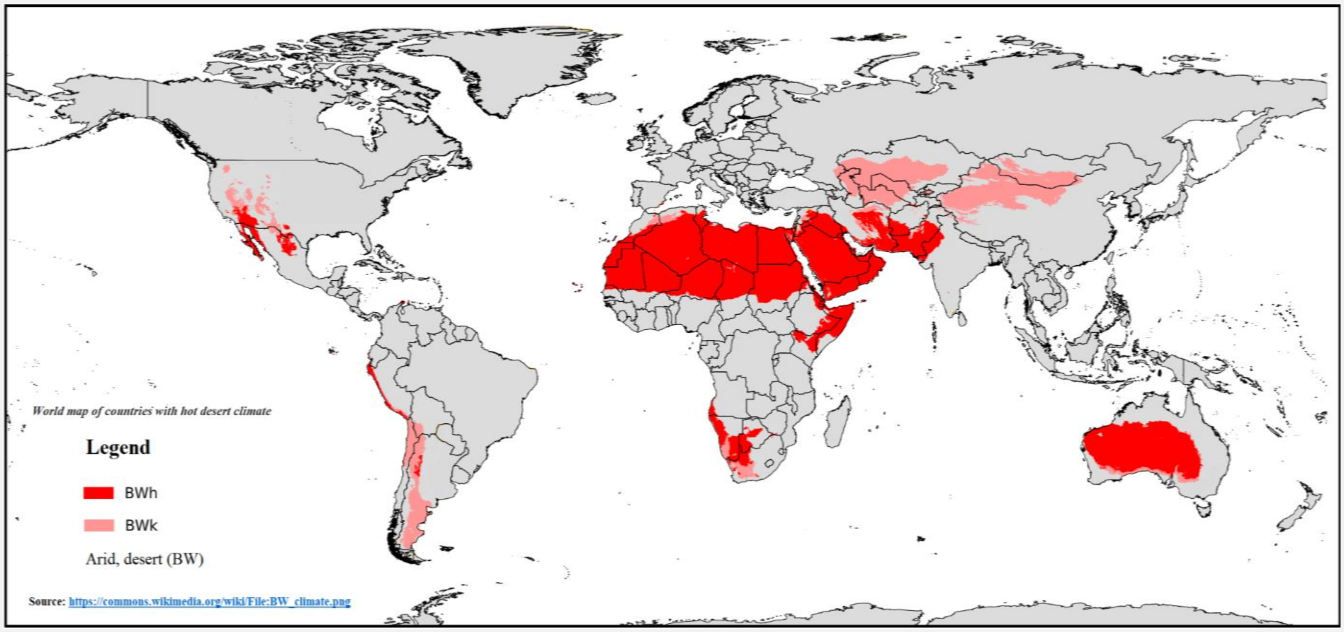

Figure 2. World Map Showing Countries with Hot Desert Climate (BWh)

Source: Lucioni, 2019

Supply augmentation through desalination has its own problems. The volumes of desalinated water in the GCC countries increased by 77 percent during the period 2010–2020 and went from 3,585 Mm3/year to 6,354 Mm3/year (Gulf Cooperation Council, 2020). Household water consumption is among the highest at the global level with 263 l/cap/day in Saudi Arabia and up to 500 l/cap/day in Kuwait, UAE, and Qatar (World Bank, 2022). The major environmental problem is brine, the hot high-salty water resulting from desalination. The rejection of brine back into the sea causes environmental impacts on the marine environment, which have been and still are ignored. Treated and sometimes insufficiently/untreated wastewater are rejected in natural channels causing groundwater degradation and seawater pollution. Although several courses in colleges of engineering and agriculture deal with water issues, the focus of such courses remains purely technical. Hence, these problems require an economic, policy, and social approach to complement students learning.

Water economics and policy in a desert environment is taught in Oman since 2011. It is a three-credits elective, taught at the undergraduate 3000 level in the form of lectures and lab work with the support of videos and flipped classroom. The course recruits students from the Department of Natural Resource Economics as well as students from the Department of Soils, Water, and Agricultural Engineering. The prerequisite for enrollment is "principles of economics," a college required course. The maximum number of students allowed in this course is 30, but this limit has never been reached and often I have around 10–15 students. The course lasts for 15 weeks. During the last three weeks, each student presents to the class a scientifically published paper on the main issues related to the course. The students are graded on a 2-hour midterm (30 percent), 1-hour presentation to the class (30 percent), and a 3-hour final exam (40 percent). The students' presentations encourage students to master self-learning, get used to life-long learning activities, apprehend water policies, and learn from other countries' successful experiences. The students can gain extra marks to encourage participation in the debates and enrich the discussions. The eight chapters of the course are as follows: (1) Introduction to Water Economics and Policy; (2) The Fundamental Economic Theory Applied to Water; (3) Water Policy Analysis; (4) Demand Analysis; (5) Water and Wastewater Pricing; (6) Water and Economics in GCC and in Oman; (7) Water Pollution and Pollution Control; and (8) Water-Energy Nexus.

The course addresses the following six major issues: water scarcity at the global level and the supply versus demand options; managing domestic water demand via pricing, quantity restriction, and technology adoption to reduce and recycle water; managing agricultural groundwater in a context of aquifer over-abstraction and seawater intrusion; traditional water markets among farmers and their possible extension to encompass trade with municipalities, including treated wastewater; the water-energy nexus, desalination for agriculture; and the transition toward the use of renewable energy and environmental impacts of desalination. The course outline is found in Annex 1.

2 Water Scarcity at the Global Level

It is fundamental that students apprehend that water scarcity is a global problem and understand the physical and social characteristics of water. The report "Charting our Water Future" clearly summarizes the current and future supply and demand for water (2030 Water Resources Group 2009). The central idea is to highlight the challenges of supplying urban water and feeding the growing population without additional water and exploring the available options for doing so. The volume of rainfall received annually on planet earth does not change (Shiklomanov, 1998). At the local scale, annual rainfall changes, leading to uncertainty. The term no additional water refers to conventional water resources. Desalination is one of the solutions to scarcity, and it is the most expensive supply expansion method. Furthermore, desalination is possible only in case seawater or brackish water is available. For many landlocked countries around the globe, even desalination is not a solution since access to seawater or brackish water is not possible. In some other cases, access to the sea is available but still desalination is not feasible. A good example is Windhoek, the capital city of Namibia, which, having an arid climate, has been recycling its wastewater into drinking water since 1968. The city is 987 km away from the sea, making it extremely expensive to transport the water after desalination. Water is heavy, and its transportation and distribution requires heavy infrastructure and a lot of energy for pumping and pressurization. Simply said, humans cannot produce water, which is a natural resource. Humans can increase supply of fresh water by purifying nonconventional water resources and accelerating the water cycle. However, that requires a lot of energy; most of it is fossil fuel at the current state of knowledge, very expensive, and not affordable for most developing countries. In desert environments, rain is extremely scarce, and only 1 percent of the rain ends up in aquifers, while 70 percent evaporates due to the high temperatures. Evaporation is around 2,000 mm/year, which is 2,000 liters/m^2/year. The remaining 29 percent of the received rain ends up as surface run-off, and only a small part is captured into dams to enhance aquifer recharge given the topography and absence of deep valleys. The cost of supply increase through recharge dams is also quite high. Nonetheless, it remains less expensive than desalination in several cases, essentially if the negative externalities of desalination are taken into account.

3 Managing Domestic Water Demand

Domestic water demand in desert areas such as GCC countries is very high despite the acute scarcity of water. Hence, demand-side policies are a top priority in teaching water economics. Historically, people living in desert environments used to use water very efficiently at all levels adjusting to scarcity (Saeid et al., 2016). Utilities in the modern states supply water to households at very cheap rates, sometimes as low as \$0.08/m^3, representing less than 7 percent of the cost, as was the case in Saudi Arabia (McIlwaine & Ouda, 2020). The relatively high incomes of the citizens is another explanatory variable of the very high water demand in the region.

On another hand, there is considerable public resistance to water price reforms and a lack of advocacy from the public authorities on the total cost of water and the amounts of subsidies allocated to the water sector, which impeded reforms. In some Islamic countries, biased culture led to thinking that water should be free. Indeed, in general, the Islamic culture calls for a sane use of water. In Islam access to public water in rivers, springs, and streams, on which there is no property rights, is free, similar to any other natural resource that is not privately owned. However, most Muslim scholars agree that water delivered to households has gone through treatment, transportation, and pressurization, which represent added values that should be priced and that water can be even traded (Kadouri et al., 2000). Many citizens in GCC see low water prices as a way to distributing the oil rent. However, citizens ignore that subsidies for water benefit more the rich than the poor (Kotagama et al., 2017). Hence, water subsidization is a biased way to distribute oil wealth. This part of the course is essentially based on Griffin (2016, pp. 145-174), where students learn the fundamentals of economic theory applied to water, derivation of water demand functions, and comparison of urban water policies. The methods learned are applied to estimate the water demand function for Muscat city using the data by Kotagama et al. (2017) and exposure to new methods using data from water utilities with a large number of observations and linked to census data providing household characteristics (Baerenklau & Pérez-Urdiales, 2019; Boland & Whittington, 2000).

Estimating the cost of the water and rate setting is discussed prior to addressing the pricing methods (Griffin, 2016; Raftelis, 2005). The conflicts of objectives among the pricing criteria are highlighted (Garrick et al., 2020). Three major stakeholders have their say on water prices: utility managers, politicians, and water users. Cost recovery and budget balance is paramount for the utility managers. However, from an economic perspective, economic efficiency and balancing supply and demand are very important objectives to achieve through pricing. Policy makers are interested on equity and fairness issues. Recent pricing methods, made possible due to data management, go beyond the classical methods such as tiered block pricing. Available detailed data on household characteristics such as income, family size, and water use allow a better compromise between the fairness and efficiency objectives (Cook & Whittington, 2020; Dinar et al., 2015).

Water prices change rarely in GCC countries, and if ever, the objective is often to reduce subsidy and balance a utility's budget with no intentions to reduce demand (Zekri, 2020). The low oil revenue and public budget deficits, in recent years, triggered cutting down the water subsidies. Nonetheless, supply increase is the rule, and construction of new desalination plants is a major task of the public water authorities. We compare quantity restrictions and pricing policy using a policy matrix. The students learn the pros and inconveniences of each policy. A quantity restriction policy though looks easier to implement, is in fact very difficult to monitor, and requires extra monitoring costs. Houses are fenced in GCC countries, and it is not even possible to monitor a policy that obliges users to reduce outdoor water and garden irrigation. Implementation of a quantity restriction on a proportional basis might end up obliging efficient water users to further cut down their consumption resulting in high marginal benefit losses.

The course addresses the limitations of water conservation via the use of education programs and awareness rising. In a review paper on behavioral change for water conservation, (Sezer et al., 2017) identified only 12 studies out of 52 reviewed, having had field experiments lasting one year or longer. Most of these studies were carried out in developed countries (United States, Germany, Switzerland, The Netherlands, Australia, Japan, Spain, and Greece). The long-term effects of behavior change on water conservation are not conclusive. Out of three types of behavioral tactics: reflective, semi-reflective, and automatic, only the first two tactics were tested with water. Information campaigns often are used during periods of water stress, are combined with price incentives, and curtailment achieve temporary water savings but appear to be inefficient in achieving long-term water conservation. For countries depending on renewable water resources, reducing water demand in the long term might not be an objective, as this would influence water rates. However, for countries depending totally on desalination, as is the case of desert countries, the long-term decrease of water demand should be an utmost goal. Data driven allowing targeted personal messages based on smart metering/real-time information compares water consumption among users evokes a feeling of discomfort and leads to short-term savings while for longer-term behavioral change the literature is inconclusive. Sønderlund et al. (2016) have studied the effect of smart metering and information feedback on domestic water saving. They reported that behavioral change depended on the feedback information, its frequency, and granularity. Most importantly, their results show that water saving is more effective when feedbacks are combined with time-variable water prices (Zekri & Al-Maamari, 2020).

Domestic water demand depends heavily on the existing fixed appliances in the home (flush toilets, faucets, garden irrigation system). A successful strategy for water demand management and permanent demand reduction requires a combination of several tools: proper rate setting, water pricing, targeted subsidy, information to users, and technology adoption. Strong price signals are necessary but not sufficient. Additionally, water users need precise, short, practical, and timely advices on how to cut down water consumption and the type of technology to adopt. Recent technology developments, such as aerators, sensors, low flow faucets/showers, smaller dual flush toilets, and timer for garden irrigation or smart irrigation systems have the advantages to provide the same utility (comfort) while reducing the volume of water used. The adoption of automated/smart garden irrigation contributes also to saving the owner's time by eliminating the need to water the plants.

Quality precise information is very helpful in achieving demand cut down. It is possible to achieve a reduction of demand at no cost in some cases. For instance, inserting a filled plastic bottle of water into an existing flush toilet is cost free and reduces water use by 1.5 liters when flushing the toilet. It requires no investments nor plumbing costs. Hence, advocacy, awareness raising, and provision of precise advice improves adoption of cost-free or low-cost technologies. However, in many other cases water-efficient technologies are uneconomical compared to their less-efficient alternatives and require legal interventions as well. For instance, only low volume/dual-flash toilets should be allowed in the market; new residences should be equipped with at-home greywater treatment facility for water recycling in gardening. This is because it is much cheaper to install a grey water facility during the construction than retrofitting one (Zekri et al., 2021). Some countries are applying rebate programs to speed up household adoption of water saving technologies and facilitating the access to such technologies. Rasoulkhani et al. (2018), using an agent based modelling approach, showed that rebate programs increase by 50 percent the rate of adoption of expensive technologies. Similarly, (Pérez-Urdiales & Baerenklau, 2019) showed that rebate programs increased adoption to levels that would not have happened without the programs, both for indoor and outdoor technologies, and that the latter have also increased the adoption of unsubsidized water-efficient technologies.

4 Managing Agricultural Groundwater

4.1 Groundwater in Desert Environments

Groundwater is the only conventional water resource in desert environments, characterized by the absence of rivers and surface reservoirs. Some of the aquifers are nonrenewables, and their management should be similar to mining oil reservoirs. The renewable aquifers are most important and more challenging to manage. In desert countries, agricultural land is not a constraint while water is the major constraint for food production. Agriculture depends totally on irrigation; rain-fed farming is not possible. Supply of the urban water is from desalination plants, and the major users of aquifers are farmers.

4.2 Aflaj

Tapping groundwater was traditionally achieved through horizontal wells (Aflaj or Qanats) that preserved aquifers from over-abstraction (Figure 3). Aflaj and Qanats flows varied according to the water elevation in the aquifers, which in turn depend on rain and natural recharge. The annual/seasonal irrigated areas increase/shrink according to the flows. The abstracted flows are allocated among users through properly defined water rights. The modern state supplied electricity to the rural areas, often at

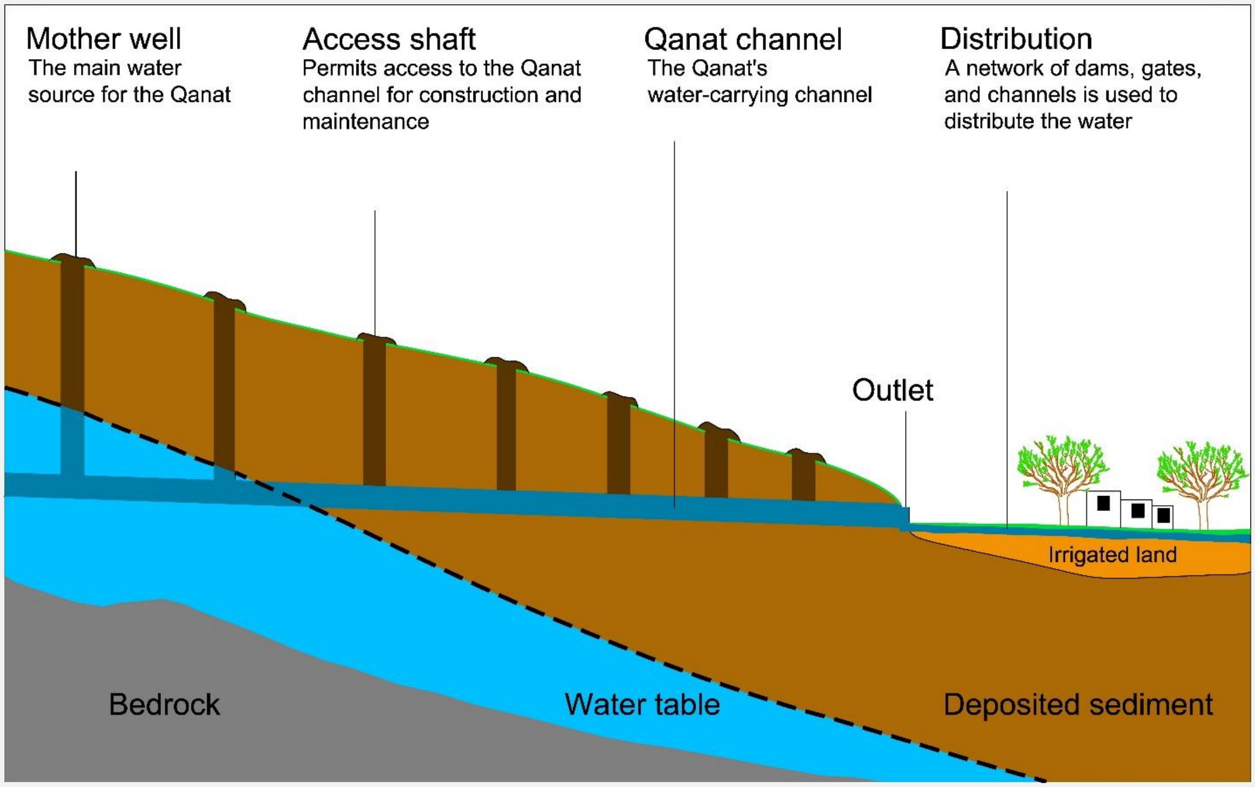

Figure 3. Falaj or Qanat Cross-Section System Tapping Groundwater

cheap prices. The public authorities encouraged the drilling of new wells and installation of electro-pumps aiming to increase food production and food security. Aquifers ended up being over-abstracted, and in the case of coastal aquifers, groundwater quality has become saline due to the seawater intrusion (Zekri & Al-Marshudi, 2008).

4.3 Aquifers Over-Abstraction

The major cause of groundwater over-abstraction, at the global level not only in desert countries, is the absence of water property rights or individual quotas. Aquifers were managed properly during centuries prior to the introduction of uncontrolled electro-pumps, which tap the groundwater without accounting for the natural recharge volumes. The course exposes students to the solution to over-abstraction from an institutional point of view in the form of allocation of property rights to the resource among the different users. The difficulties to monitor abstraction are a major cause of the implementation of such an approach. Hence, adoption of new technologies at an aquifer level are shown as an example to address the feasibility of the establishment of water quotas in combination with the installation of groundwater smart meters and online monitoring.

4.4 Managing Aquifers

The course exposes the students to the methodological approaches for an efficient use of groundwater. Dynamic optimization models, applying the Hotelling principle, coupled with aquifer simulation models such as MODFLOW are used to determine the optimal annual abstraction volume from an aquifer and agent-based modelling to allocate such volumes among users (Zekri et al., 2017). Sustainability implies cutting down the abstraction. Reduction of abstraction does have implications on wealth distribution, and the social and political issues are important. To attenuate the negative social impacts we recommend mechanisms to compensate farmers who will have to quit the business. The course addresses the groundwater quality, caused by over-abstraction. Indeed, when aquifers are located on coastal areas, the salinization of the aquifers is higher the closer the farmland to the sea. In oil-dependent countries such as GCC, farming is most often a secondary activity, making it easier to transition to a sustainable use of the aquifers as the social impacts are less acute and funds for compensation are relatively easier to find. Another way of compensating farmers consists of allowing land use change from agricultural to urban uses, avoiding any governmental payment to farmers to withdraw from groundwater pumping. Finally, the adoption of more efficient irrigation technologies, in the absence of water pricing or individual quotas, cannot resolve the over-abstraction issue. Farmers adopting the water-saving technology tend to expand the irrigated land and/or intensify the production within the same land within the seasons (Zekri & Al-Marshudi, 2008). An advanced theoretical explanation of the effect of irrigation technology subsidy and water pricing on groundwater pumping is found in (Wang et al., 2015).

4.5 Aquifers' Storage and Recovery

Aquifers are perfect nature-based storage facilities. Aquifers provide free storage capacity; protect groundwater from evaporation and to a certain point from pollution. Urban water security in the GCC countries is very low, and the building of concrete reservoirs results in a high cost per cubic meter stored. The over-abstraction not only results in the salinization of coastal aquifers, but it also reduces the aquifers' storage capacity through land subsidence. In addition to the allocation of water quotas, aquifers storage and recovery represents a formidable solution that enhances water security, avoids seawater intrusion, and protects the storage capacity. This course applies an integrated water management approach of desalinated water and groundwater and exposes students to the economic modelling of injection and abstraction of desalinated water and its benefits in an uncertain environment (Al-Maktoumi et al., 2021; Zekri et al., 2021).

5 Traditional Water Markets and Their Expansion

The second aspect related to aquifer management emanates from the use of the groundwater essentially to farming. Theoretically, water should be flowing first to those who are ready to pay higher prices for it, that is urban users. While traditionally in desert environments the top priority of groundwater is providing drinking water, the situation has been reversed. Water markets are a possible way to restore the priority of water use. Water markets among farmers are spread and still operational in rural Oman for instance. The existing water markets allowed securing roughly the necessary funds for a proper maintenance of the water infrastructure. Voluntary work, from the Aflaj (plural of Falaj) communities, supplied the labor force for the maintenance whenever it was necessary, and extra funding from the villagers during urgency was a common practice (Zekri & Al-Maamari, 2020). However, given the fact that the villages' domestic water depends no more on Aflaj, the voluntarism shown by households to restore a damaged channel of the Falaj is fading. Restoring the damaged channel was essential for survival (drinking, cooking, and hygiene). Currently, groundwater is almost exclusively used for farming, and the urgency for restoring the flows, in case of collapses, is no longer felt, as even farming is a hobby/secondary activity. This is partly a result of public interventions, bringing piped water, which is causing a slow degradation of Aflaj's infrastructure that has been preserved for millennia.

The majority of Aflaj are located quite far away from the coastal land, and many of them are in mountainous areas. Hence, the cost of transporting piped water until these rural locations is high both in terms of initial investments as well as in terms of operating and maintenance costs. It is an energy intensive process. In essence, the Aflaj water laws give utter priority of water allocation to the domestic uses. In the past, domestic uses were very small, compared to the agricultural demand, as households were allowed to take water from the sources but not to divert the source to their residences. There was no piped water in the villages, and farmers privately own groundwater. The creation of water markets between Aflaj (agriculture) and the cities increases the benefit of farmers and the city simultaneously and enhances the sustainability. Hypothetical, markets between farmers and the city are considered. Farmers, who are the water shareholders, can sell part of the Aflaj water to the city and buy tertiary/quaternary treated wastewater from the treatment plant. Aflaj water is of much higher quality than the treated wastewater; hence in the exchange, farmers will gain financially. The city, or water utility, will also gain since buying the water from Aflaj is much cheaper than buying and transporting desalinated water from faraway coastal areas. This allows recycling the tertiary/quaternary treated wastewater and sustaining the agricultural activity. The wastewater company can recover an important part of the treatment cost, which will enhance its financial sustainability. Most of the treated wastewater is currently disposed of in the Wadis (channels that are dry except in the rainy season) and is not generating any returns. Establishing the water markets require revising the water institutions to allow trade between farmers and the city. To facilitate such revision, students learn how to estimate the long run benefits to each party: city, farmers, and the treated wastewater company. While the estimation of benefits could facilitate water trade, a social approach to persuade farmers of the unsustainable current practices of supplying desalinated water and reviving the historical principles of Aflaj management would weaken any resistance against trade. In Muscat city, all parks and landscapes are irrigated from treated wastewater. Citizens are progressively accepting the treated wastewater re-use. Many agricultural products irrigated with treated wastewater, imported from Jordan and other countries, are sold in the GCC countries. Progressively the social resistance to treated water recycling is diminishing. The advantage of water markets, among cities and Aflaj, is that the farmers will be properly compensated through the transactions. Finally, not all groundwater will be transferred to cities as the demand is not that high. Hence, consumers looking for local agricultural products irrigated with fresh water will always find them.

6 Water-Energy Nexus, the Transition Toward the Use of Renewable Energy and Desalination for Agriculture

Desalination is an energy-guzzling process currently met by fossil fuels. Desalination is simply changing the scarcity from the water sector to the energy sector. For instance, Darwish et al. (2008) alarmed on the consumption of electricity and desalinated water in Kuwait and their high growth rates. They estimated that all of Kuwait's oil production will be used to produce water and electricity in about thirty years to satisfy demand. Although their estimations are based on constant technology assumptions, the desalination is causing stress on the energy sector. In Saudi Arabia, 3.4 million barrels of oil equivalent are burned daily out of which 10 to 20 percent are used for desalination as of 2010 (Rambo et al., 2017). Although the desalination technology did improve during the last decade, reverse osmosis, the most efficient technology, compared to multistage flash and multi-effect desalination, uses 3.5 to 5.0 kWh of electricity per cubic meter depending on the size of the plant and the salinity of the intake water. The supply augmentation of desalinated water increases the domestic consumption of oil and gas and reduces the revenue from the oil sector, the main source of income.

The use of renewable energies for desalination is still in its infancy and is applied at small-scale plants. Costs of desalination using renewables vary considerably according to the type of renewable energy used and plant capacity. For instance, for seawater reverse osmosis combined with photovoltaic solar power, the cost is 11.7–15.65 $\$/m^3$ (Bundschuh et al., 2021). Most of the innovations are undertaken at research centers and universities. Large desalination companies often benefit from a highly subsidized cost of energy that in turn discourages innovations for the transition toward renewables (England & Al-Atrush, 2022). Students are taught that West Australia enacted regulations, for new desalination plants, to use renewable energy sources (Knights et al., 2007); https://www.energymatters.com.au/renewable-news/em515/).

Small desalination units is a decentralized solution to water supply compared to the current highly centralized plants. Several options exist in the market for family level or village level. Solar stills are the simplest devices to desalinate water, utilizing direct solar radiation, for low capacity water supplying systems in remote areas. The solar still is based on the principle of evaporation and condensation process. Hydro-panels is a technology that produces water for houses or the village/district level. A hydro-panel is a combination of solar panels and a system that harvests water drops from the air (Ferwati, 2019). The costs of desalination are high but could be a good alternative for remotely located houses for drinking and cooking purposes only. Some of these options are available in the market, and prices vary from $0.0066 to $0.30 per liter (Zekri & Al-Maamari, 2020). Standalone systems represent new water supply systems for remote areas with dispersed population. In some circumstances, the savings on network connections make the standalone system profitable.

The course addresses the feasibility of desalination water for irrigation purposes. Very few farmers in the GCC have adopted small desalination units, often to overcome the salinity problem of the groundwater. The course goes beyond estimation of the costs and benefits to farmers. Students' attention is called on international trade of agricultural products, or virtual water, as an alternative to groundwater abstraction and desalination (Kajenthira Grindle et al., 2015; Ouda, 2014). In fact, given the economic openness of most GCC countries to international trade, desalination for irrigation has little room, despite the electricity price subsidy, except for hobby farms. Local products require substantial volumes of water due to the extremely hot environment and hence are not competitive with imports (Al Jabri et al., 2019). Finally, yet importantly, the desalination units place more stress on the electricity grid during summer's peak hours, and the negative impacts of disposal of the brine into the aquifers causes further degradation of the groundwater quality.

7 Environmental Impacts of Desalination

Often the water sector calls for a high initial investment cost followed by a very long pay-back period. This is quite different with desalination plants as they are capital intensive but their expected life is 20–30 years. These plants depreciate within a single generation and do not span to future generations like dams or water pipes. Hence, the appetite of the private sector to invest in desalination plants with long-term contracts (take-or-pay) with fixed prices labelled in hard currencies and volumes clearly specified and agreed on. Private companies are selected on one criteria: the lowest desalination cost. The negative externalities are not taken into account for the selection. This type of contract encourages a supply policy approach and discourages the desalination companies to cut down their negative impacts or even to innovate and find better solutions to the process of desalination in a way that it is less harmful to the marine environment. Fortunately, public authorities in developed countries are starting to realize that the environmental impacts are of concern. Recently in California, the Coastal Commission unanimously voted against the construction of a new desalination plant in Huntington Beach. The rejection was based on the negative impacts on marine life, the high costs to the water users, and the choice of the location and lack of near-term need of the water (Phys.org, n.d.).

However, the water authorities and desalination plants in the GCC countries are still behaving as if seawater in the Arabian Gulf is unlimited and the negative externalities are minimal. Although for each new desalination project, an environmental impact assessment is ordered, in reality the cumulative impacts of the different plants and other economic activities are never considered. Eight countries are bordering the Arabian Gulf. In addition to the pollution from desalination plants, the other economic activities are also contributing to the pollution among which the power plants, the oil industry, and transportation are the most polluting.

Most GCC countries withdraw seawater for their desalination plants from the Arabian Gulf or Red Sea. le Quesne et al. (2021) affirm that the environmental impacts caused by the brine disposal loaded with chemicals, used as anti-fouling and membrane cleaning, as well as the loss of marine life through seawater intake to the process are of high concerns in the Arabian Gulf. The desalinated volumes from plants based on the Arabian Gulf increased from 0.04 million m^3/day in 1970 to reach 21 million m^3/day in 2018. For every desalinated 1 million m^3 plants pump 2.3 million m^3 from the sea, as water feed intake. Hence, 1.3 million m^3 return back to the sea in the form of brine. The impacts of brine are essentially due to the high level of salinity; low level of oxygen content, chemicals, and total alkalinity; and high temperature. The average salinity in the Arabian Gulf reached over 39 parts per thousand (ppt), and it is predicted that it will rise to 70 ppt in low flashing and shallow embayment. The salinity of seawater in the east side of Qatar is already around 45 ppt, and for the west side it is 57 ppt, which is comparatively higher than the other regions. Reverse osmosis can tolerate a maximum feed water salinity of 70 ppt (Panagopoulos, 2021). Observe that the higher the salinity of the seawater, the higher the cost of desalination. Not only future costs of desalination will increase, due to higher energy requirements, but most importantly the predicted temperature increases, caused by the brine disposal, could lead to significant impacts on species persistence, biodiversity, fisheries productivity, and coastal communities (le Quesne et al., 2021). The sought economic diversification and the transition to an economy independent from fossil fuels will require the preservation of the natural capital (sea and marine environment), in the instance of the Arabian Sea, on which several economic activities (tourism, recreation, fishing, diving, etc.) rest. There is need for major changes to ensure the sustainable use of the Arabian Gulf. The cost of water does not take into account the negative externalities caused by brine disposal. There is an absence of studies valuing these environmental impacts. Most of the existing studies dealt with physical and biological impacts such as the water temperature increase, the salinity increase, bleaching of coral reef, and the loss of marine biodiversity (Campos et al., 2020; Ibrahim & Eltahir, 2019; Sezer et al., 2017).

Panagopoulos and Haralambous (2020) summarized several studies that addressed the reduction or the elimination of the brine. Among the solutions, several will only transfer the pollution problem to other resources, such as groundwater, surface water, or land. It is stressed that the evaporation of the brine is the least polluting method and the most expensive, with costs ranging between \$3.28 and \$10.04/m^3. Production of table salt is among the products considered. Every cubic meter of brine produces 70 kg of salts. If all brine in GCC countries is evaporated, production of table salt would exceed 2 million tons/day, which will find no market to absorb it.

The total elimination of brine disposal, by evaporation or other means, though environmentally very sound, is not currently economically feasible, as it will increase drastically the cost of desalination. Hence, chances for desalination plants to adopt the zero liquid discharge are remote. It will be hard for public decision makers, depending on desalination from the Arabian Sea, to agree on the future brine policy to adopt. At current state-of-the-art, the cost of brine disposal is three to ten times the cost of desalinating the water. How much of the brine disposal cost can be charged to water users remains a question. An important step in terms of policy is that in the future, contracts with desalination companies should consider the negative externalities as one more criteria in the selection process. This would encourage companies operating in the sector to speed up innovations and cut down the cost of brine disposal.

8 Conclusions

Teaching water economics in desert regions is oriented toward demand management policies given the acute water scarcity. Issues related to rate setting, water pricing, quantity rationing, and technology adoption are of prime importance for the management of urban water. Supply of desalinated water represents an important part of the GCC countries' public expenditures. The course addresses groundwater, the only renewable water resource, through the lenses of property rights, smart metering, and quota allocations as well as international food trade and/or virtual water imports. The course exposes the students to the limits of desalination as a source of fresh water and the environmental costs it generates. Supply of desalinated water depends on the availability and access to a brackish source or seawater.

The increased salinity of the Arabian Sea and the increase in the temperature of the seawater are a worry for the six countries depending on it as a source for desalination. The increase of the seawater salinity has a direct impact on the cost of desalination. The loss of marine life, biodiversity, fish diversity, and harvest all negatively affect the sustainability of the sea as a natural resource, which is supposed to be the basis for economic diversification in the region.

There is an urgent need of policy changes that would foster the transition toward the integration of renewable energies in desalination. Currently, the public water authorities select the private desalination companies on the least cost supply of fresh water. Minimization of the environmental brine impacts is equally important as the cost of water from a sustainability point of view.

The main messages from the course are the need to reduce water demand (reduce waste) to much lower levels, without causing a loss of utility or comfort. Pricing and quantity restriction are variables that water managers' control to influence users' water demand. The course discusses the issues of access of water to the poor, in developing countries, and of fairness in general. The students learn about new pricing methods that take into account the households' revenue and family size. The course strongly recommends the transfer of some of the agricultural water to urban uses, whenever economically feasible, through water markets and the recycling of the treated wastewater in irrigation. Policies that foster the transition from a supply side to a demand side are the core of the course.

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References

2030 Water Resources Group.(2009) . Charting Our Water Future: Economic Frameworks to Inform Decision-Making. 2030 Water Resources Group. https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/pdfs/charting%20our%20water%20future/charting_our_water_future_full_report_.ashx

Al Jabri, S. A., Zekri, S., Zarzo, D., & Ahmed, M. (2019). Comparative Analysis of Economic and Institutional Aspects of Desalination for Agriculture in the Sultanate of Oman and Spain. Desalin. Water Treat, 156, 1-6. https://doi.org/10.5004/dwt.2019.24066

Al-Maktoumi, A., Rajabi, M. M., Zekri, S., & Triki, C. (2021). A Probabilistic Multiperiod Simulation–Optimization Approach for Dynamic Coastal Aquifer Management. Water Resources Management, 35(11), 3447-3462. https://doi.org/10.1007/s11269-021-02828-0

Baerenklau, K. A. & Pérez-Urdiales, M. (2019). Can Allocation-Based Water Rates Promote Conservation and Increase Welfare? A California Case Study. Water Economics and Policy, 5(02), 1850014. https://doi.org/10.1142/S2382624X18500145

Boland, J. J., & Whittington, D. (2000). Water Tariff Design In Developing Countries: Disadvantages of Increasing Block Tariffs (Ibts) and Advantages of Uniform Price with Rebate (UPR) Designs. World Bank Water and Sanitation Program, Washington, DC, 37.

Bundschuh, J., Kaczmarczyk, M., Ghaffour, N. & Tomaszewska, B. (2021). State-of-the-Art of Renewable Energy Sources Used In Water Desalination: Present and Future Prospects. Desalination, 508, 115035. https://doi.org/10.1016/j.desal.2021.115035

Campos, E. J. D., Vieira, F., Cavalcante, G., Kjerfve, B., Abouleish, M., Shahriar, S., Mohamed, R. & Gordon, A. L. (2020). Impacts of Brine Disposal from Water Desalination Plants on the Physical Environment in the Persian/Arabian Gulf. Environmental Research Communications, 2(12), 125003. https://doi.org/10.1088/2515-7620/abd0ed

Cook, J. & Whittington, D. (2020). Editorial-Water Tariffs and Affordability: The Economics and Policy of Protecting the Poor. Water Economics and Policy, 6(3). https://doi.org/10.1142/S2382624X20020014

Darwish, M. A., Al-Awadhi, F. M., & Darwish, A. M. (2008). Energy and Water in Kuwait Part I. a Sustainability View Point. Desalination, 225(1-3), 341-355. https://doi.org/10.1016/j.desal.2007.06.018.

Dinar, A., Pochat, V., & Albiac-Murillo, J. (Eds.). (2015). Water Pricing Experiences and Innovations, (Vol. 9). Switzerland, Cham : Springer International Publishing. https://doi.org/10.1007/978-3-319-16465-6

England, A., and S. Al-Atrush. (2022). Saudi Arabia's Green Agenda: Renewables at Home, Oil Abroad. Financial Times, November 22.

Ferwati, M. S. (2019). Water harvesting cube. SN Applied Sciences, 1(7), 779. https://doi.org/10.1007/s42452-019-0730-y

Garrick, D. E., Hanemann, M. & Hepburn, C. (2020). Rethinking the Economics of Water: an Assessment. Oxford Review of Economic Policy, 36(1), 1-23. https://doi.org/10.1093/oxrep/grz035

Griffin, R. C. (2016). Water Resource Economics: The Analysis of Scarcity, Policies, and Projects. MIT Press, Cambridge, Massachusetts, London, England

Gulf Cooperation Council. (2020). Water Statistics in GCC. Desalination Statistics. Table 4. https://www.gccstat.org/en/statistic/statistics/environment

Ibrahim, H. D. & Eltahir, E. A. B. (2019). Impact of Brine Discharge from Seawater Desalination Plants on Persian/Arabian Gulf Salinity. Journal of Environmental Engineering, 145(12), 04019084. https://doi.org/10.1061/(asce)ee.1943

Jomehpour, M. (2009). Qanat Irrigation Systems as Important and Ingenious Agricultural Heritage: Case Study of the Qanats of Kashan, Iran. International Journal of Environmental Studies, 66(3), 297-315. https://doi.org/10.1080/00207230902752629

Kadouri, D. Y., Djebbar, Y. & Nehdi, M. (2000). Water Rights and Water Trade: an Islamic Perspective. Water management in Islam,. United Nations University Press, Tokyo, 85-93

Kajenthira Grindle, A., Siddiqi, A. & Anadon, L. D. (2015). Food Security Amidst Water Scarcity: Insights on Sustainable Food Production from Saudi Arabia. Sustainable Production and Consumption, 2, 67-78. https://doi.org/10.1016/j.spc.2015.06.002

Knights, D., MacGill, I. & Passey, R. (2007). The Sustainability of Desalination Plants in Australia: is Renewable Energy the Answer? Ecological Engineering, OzWater Conference, Sydney. http://equatica.com.au/pdf/Knights,%20MacGill%20and%20Passey%20OzWaterpaperIMRP_000.pdf

Kotagama, H., Zekri, S., al Harthi, R. & Boughanmi, H. (2017). Demand Function Estimate for Residential Water in Oman. International Journal of Water Resources Development, 33(6), 907-916. https://doi.org/10.1080/07900627.2016.1238342

le Quesne, W. J. F., Fernand, L., Ali, T. S., Andres, O., Antonpoulou, M., Burt, J. A., Dougherty, W. W., Edson, P. J., el Kharraz, J., Glavan, J., Mamiit, R. J., Reid, K. D., Sajwani, A. & Sheahan, D. (2021). Is the Development of Desalination Compatible with Sustainable Development of the Arabian Gulf? Marine Pollution Bulletin 173, 112940. https://doi.org/10.1016/j.marpolbul.2021.112940

Lucioni, M. 2019. File: BW climate.ong. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:BW_climate.png.

McIlwaine, S. J. & Ouda, O. K. M. (2020). Drivers and Challenges to Water Tariff Reform in Saudi Arabia. International Journal of Water Resources Development, 36(6), 1014-1030. https://doi.org/10.1080/07900627.2020.1720621

MRMWR. (2008).Aflaj oman in the World Heritage List. Muscat, Oman. Ministry of Regional Municipalities and Water Resources-MRMWR.

Ouda, O. K. M. (2014). Impacts of Agricultural Policy on Irrigation Water Demand: a Case Study of Saudi Arabia. International Journal of Water Resources Development, 30(2), 282-292. https://doi.org/10.1080/07900627.2013.876330

Panagopoulos, A. (2021). Water-Energy Nexus: Desalination Technologies and Renewable Energy Sources. Environmental Science and Pollution Research, 28(17), 21009-21022. https://doi.org/10.1007/s11356-021-13332-8

Panagopoulos, A. & Haralambous, K. J. (2020). Environmental Impacts of Desalination and Brine Treatment - Challenges and Mitigation Measures. Marine Pollution Bulletin , 161, 111773. https://doi.org/10.1016/j.marpolbul.2020.111773

Pérez-Urdiales, M. & Baerenklau, K. A. (2019). Additionality Effects of Rebate Programs in the Residentialwater Sector: Indoor vs. Outdoor. Water (Switzerland), 11(6), 1170. https://doi.org/10.3390/w11061170

Phys.org. (n.d.). California Coastal Commission Rejects Plan for Poseidon Desalination Plant. Retrieved 29 December 2022, https://phys.org/news/2022-05-california-coastal-commission-poseidon-desalination.html

Raftelis, G. (2005). Water and Wastewater Finance and Pricing: a Comprehensive Guide. CRC Press, Boca Raton. https://doi.org/10.1201/9781420032062

Rambo, K. A., Warsinger, D. M., Shanbhogue, S. J., Lienhard, J. H. V. & Ghoniem, A. F. (2017). Water-Energy Nexus in Saudi Arabia. Energy Procedia 105, 3837-3843. https://doi.org/10.1016/j.egypro.2017.03.782

Rasoulkhani, K., Logasa, B., Reyes, M. P. & Mostafavi, A. (2018). Understanding fundamental Phenomena Affecting the Water Conservation Technology Adoption of Residential Consumers using Agent-Based Modeling. Water (Switzerland), 10(8), 993. https://doi.org/10.3390/w10080993

Reddy, K. V. & Ghaffour, N. (2007). Overview of the Cost of Desalinated Water and Costing Methodologies. Desalination, 205(1-3), 340-353. https://doi.org/10.1016/j.desal.2006.03.558

Saeid, E., A. Davari, and M.N. Reyhani. (2016). Iranian Qanāts: An Ancient and Sustainable Water Resources Utilization. Underground Aqueducts Handbook. CRC Press, Boca Raton. 123–150. https://doi.org/10.1201/9781315368566

Sezer, N., Evis, Z., & Koç, M. (2017). Management of Disalination Brine in Qatar and the GCC Ccountries. 10th International Conference in Sustainable Energy Environmental Protection, Bled, Slovenia. https://hdl.handle.net/11511/79623

Shiklomanov, I. A. (1998). World Water Resources : a New Appraisal and Assessment for the 21st Century : a Summary of the Monograph World Water Resources. United Nations Educational, Scientific and Cultural Organization (UNESCO): Paris, France.

Sønderlund, A. L., Smith, J. R., Hutton, C. J., Kapelan, Z. & Savic, D. (2016). Effectiveness of Smart Meter-Based Consumption Feedback in Curbing Household Water Use: Knowns and Unknowns. Journal of Water Resources Planning and Management, 142(12), 04016060. https://doi.org/10.1061/(asce)wr.1943-5452.0000703

Wang, T., Park, S. C. & Jin, H. (2015). Will Farmers Save Water? a Theoretical Analysis of Groundwater Conservation Policies. Water Resources and Economics, 12, 27-39. https://doi.org/10.1016/j.wre.2015.10.002

Williams, J. (2022). Desalination in the 21st Century: a Critical Review of Trends and Debates. Water Alternatives, 15(2), 193–217.

World Bank. (2022). Advancing the Knowledge of the Water-Energy Nexus in the GCC Countries." Water Global Practice. World Bank Group, Whashington, 81 pages. https://documents1.worldbank.org/curated/en/099355009132215715/pdf/P1768640ebe4770180b3970bccc84ae2926.pdf

Zekri, S. (2008). Using Economic Incentives and Regulations to Reduce Seawater Intrusion in the Batinah Coastal Area of Oman. Agricultural Water Management, 95(3), 243-252. https://doi.org/10.1016/j.agwat.2007.10.006

Zekri, S. (2020). The water sector in MENA region: The way forward. Global , Water Policy, 23, 185–200. https://doi.org/10.1007/978-3-030-29274-4_9/COVER

Zekri, S. & Al-Maamari, A. (2020). An Overview of the Water Sector in MENA Region. Global Issues in Water Policy, 23, 1-17. https://doi.org/10.1007/978-3-030-29274-4_1

Zekri, S. & Al-Marshudi, A. S. (2008). a Millenarian Water Rights System and Water Markets in Oman. Water International, 33(3), 350-360. https://doi.org/10.1080/02508060802256120

Zekri, S., Madani, K., Bazargan-Lari, M. R., Kotagama, H. & Kalbus, E. (2017). Feasibility of Adopting Smart Water Meters in Aquifer Management: An Integrated Yydro-Economic Analysis. Agricultural Water Management, 181, 85-93. https://doi.org/10.1016/j.agwat.2016.11.022

Zekri, S., Triki, C., Al-Maktoumi, A. & Bazargan-Lari, M. R. (2021). Optimization of Storage and Recovery of Seasonal Surplus Desalinated Water in a Coastal Aquifer. Arabian Journal of Geosciences, 14(2), 1–12. https://doi.org/10.1007/S12517-020-06340-4/METRICS

5 (3) DOI: 10.22004/ag.econ.338385