Water Resour Manage (2017) 31:781–792
DOI 10.1007/s11269-016-1419-2

Desalination of Seawater using Geothermal Energy to Meet Future Fresh Water Demand of Saudi Arabia

D. Chandrasekharam[1,2,3] **· A. Lashin**[4,5] **· N. Al Arifi**[2] **·**
A. Al Bassam[2] **· C. Varun**[3]

Received: 15 January 2016 / Accepted: 22 June 2016 /
Published online: 1 July 2016

Abstract The future economy of the Middle East countries (GDP growth) depends on the availability of fresh water for domestic and agricultural sectors. Saudi Arabia, for example, consumes 275 L/day per capita of water that is generated from desalination process using 134 x 10^6 kWh of electricity. With 6 % population growth rate, demand for fresh water from fossil fuel based desalination plants will grow at an alarming rate. It has been reported that Saudi Arabia's reliance on fossil fuels to generate electricity and generate fresh water through desalination using the same energy source is economically and politically unsustainable. This may lead to destabilisation of the global economy. However, Saudi Arabia has large geothermal resources along the Red Sea coast that can be developed to generate power and support the generation of fresh water through desalination. The cost of fresh water can be further lowered from the current US$ 0.03/m^3. Among the gulf countries, Saudi Arabia can become the leader in controlling CO_2 emissions and mitigating the impact on climate change and agricultural production. This will enable the country to meet the growing demand of food and energy for the future population for several decades and to reduce food imports.

Keywords Desalination · Geothermal · CO_2 emissions · Saudi Arabia · Food security

✉ D. Chandrasekharam
dchandra50@gmail.com

1 Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India

2 College of Science, Geology and Geophysics Department, King Saud University, Riyadh 11451, Saudi Arabia

3 GeoSyndicate Power Pvt. Ltd, Mumbai, India

4 Faculty of Science, Geology Department, Benha University, Benha 13518, Egypt

5 College of Engineering, Petroleum and Natural Gas Engineering Department, King Saud University, Riyadh 11421, Saudi Arabia

1 Introduction

Saudi Arabia covers an area of 2.15 million km^2 and is the largest country in the Arabian Peninsula. Major part of the country is arid while a part of the coastal strip along the Red Sea enjoys semi arid climate. South west monsoon brings 300 mm of rain over the south-eastern part of the country while rain fall over the rest of the country is scanty with annual rain fall of about 100 mm/y. The Empty Quarter (south south-eastern part) is absolutely dry and is a rain shadow region. The population of Saudi Arabia is 28 million with a growth rate of 6 % (Chandarasekharam et al. 2014a). A large part of the population live in urban areas with access to water and sanitation. Although the country has energy security, the country is highly stressed for water due to poor rainfall and lakh of defined river and drainage systems (Lovelle 2015). In spite of the fact that the country has only 2.4 billion m3 of renewable water resource, 20 billion m3 of water is withdrawn annually. This large quantity is withdrawn from non-renewable (fossil) groundwater deep in the sedimentary formation of Mesozoic era. This water is used for agricultural activity while the industrial and municipal sectors depend heavily water sourced from desalination (ESCWA 2001b; FAO 2008; SAMA 2010; Kajenthira et al. 2012). In spite of this water stressed situation, the country till now placed significant importance for food production. Agriculture contributes 3 % of GDP. Currently 1.73 million ha area (17,300 km^2) is irrigated that supports wheat, barley and dates cultivation. Wheat is staple food of Saudi Arabia and the percapita consumption of pita (wheat bread) is 241 g per day (88 kg per year). The total wheat consumption by Saudi Arabia population during MY (Mid Year) 2013–2014 was 3.25 million metric tonnes (Chandrasekharam et al. 2015a, b, c). Due to severe water scarcity, the government adopted a policy not to grow wheat from 2016. Thus wheat import is expected to reach 3.03 million tonnes in MY 2013–2014 compared to 1.92 million tonnes in 2012–2013 (USDA 2013, Chandrasekharam et al. 2015a, b, c). Placing the country's food security with other countries is not a sensible decision. It has been reported that Saudi Arabia's reliance on fossil fuels to generate electricity and generate fresh water through desalination using the same energy source is economically and politically unsustainable, and if this trend continues Saudi Arabia will become an oil importer in the next two decades (Ahmad and Ramana 2014), leading to destabilization of the global economy. But there is a solution to this issue that can provide the country with fresh water for all the future generations and provide the country with energy and food security. Thus energy and water issues are a cause of concern not only to Saudi Arabia but to all the Gulf Cooperation Countries. The strategy these countries adopts to address these issues will have an impact on the prosperity and quality of future life. This solution lies in the vast geothermal resources that the country has along the western Arabian shield (Chandrasekharam et al. 2015a, b, c). This energy source can bring sustainable development in energy and food sectors.

2 Water Resources Status

With scanty rainfall and lack of defined river and drainage systems, annual amount of 2200 MCM water that the surface receives infiltrates completely into the shallow aquifers. Thus the annual groundwater recharge that occurs in the western margin of Saudi Arabia is only 2200 MCM/y (FAO 2009). The agriculture sector's demand is larger than the domestic. Information on the water use between 2000 and 2010 shows that there is large demand in agricultural sector compared to domestic sector (Table 1).

Table 1 Water use in million cubic meters, Saudi Arabia (Abderrahman 2001, FAO 2009)

Year	Domestic/Industrial	Agriculture	Total
2000	2900	11,200	14,100
2004	2740	17,530	20,270
2009	3170	15,090	18,260
2010	3600	14,700	18,300

Due to decline in the aquifer yield and fall in the water table levels (Fig. 1), there is an embargo on the water consumption by the agricultural sector. The annual surface water and groundwater recharge and water consumption are shown in Table 2.

The annual agricultural water demand is 20,800 MCM/y (million cubic meter) that is 10 times larger than the domestic demand (Table 2).

The aquifers that are being targeted to extract groundwater are sandstones of Paleozoic - Mesozoic -Cenozoic eras and these waters are paleo waters (also known as formation waters) deposited along with these formations. Since there is no recharge into these aquifers, there is a drastic decline in water table due to extraction (Fig. 1). These aquifers occur at depths varying from 1000 to 2000 m below the ground level. The main aquifers that supply water to Saudi Arabia are shown in Table 3.

All the major aquifers in Saudi Arabia are trans-boundary aquifers providing water to other neighbouring countries like Jordan, Yemen, Iraq, Bahrain, Oman, Qatar and Kuwait (Table 3). Thus nearly 394 MCM/y of water flows out of Saudi Arabia into the neighbouring countries. Nearly 180 MCM/y of water flows in to Jordan from Saudi Arabia. The Saq-Ram sandstone aquifer is the largest aquifer and the significant shared aquifer in this region. Since this is one of the largest and significant aquifer with proven reserves of 103,360 MCM (Table 3), both Saudi Arabia and Jordan extensively withdraw water from this aquifer. Saudi Arabia has an MoU (memorandum of understanding) with neighbouring countries on water sharing from the aquifers shown in Table 3 (FAO 2009). According to this MoU, Jordan should withdraw only 20 MCM/y water from Saq Ram aquifer but Jordan withdraws nearly 180 MCM/y of water. Thus, because of

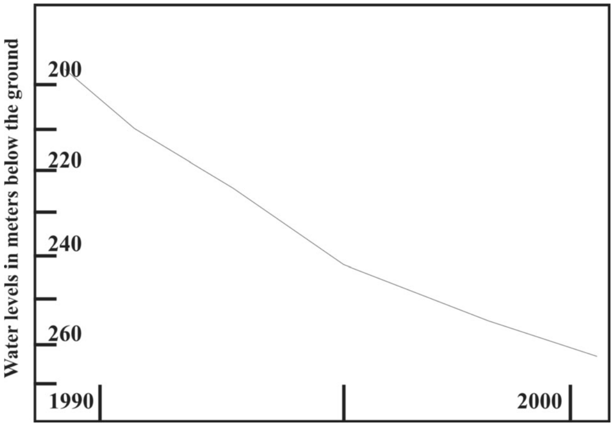

Fig. 1 Fall in the water table levels in deeper aquifers during the last decade (modified after Lovelle 2015)

Table 2 Annual water recharge and water use (FAO 2009)

Recharge	
Surface water (MCM/y)	2200
Groundwater (MC M/y)	2200
Dam (MCM/y)	99
Total per capita (CM)	97
Withdrawal	
Agri (MCM/y)	20,800
Domestic MCM/y	2130
Industry	710
Total (MCM/Y)	23,640
percapita (CM)	960
population(million)	24.6

trans-boundary aquifers the countries are on war for water and this will escalate to an ugly situation in future due to large population growth in all these Gulf countries and severe decline in piezometric surfaces. It is estimated, at the current level of abstraction, the Saq-Ram aquifer may yield water only for the next 30 years (UN-ESCAW 2013). From the Table 2 it is apparent that the withdrawal/consumption rate is much higher than the recharge and hence to meet the current demand groundwater supply is supplemented by desalinated water. At present 275 L/day per capita of desalinated water is generated using 134 x 10^6 kWh of electricity from fossil fuels (Chandarasekharam et al. 2014a, b). Reverse osmosis is commonly used for desalination process world over. However, Saudi Arabia uses thermal multistage flash distillation process that is energy intensive and requires ~10 to 12 TWh to desalinate 1 m^3 sea water (Ghaffour et al. 2014, Chandrasekharam et al. 2015c). The quantity of electricity generated during the desalination process is shown in Fig. 2. This is a very insignificant amount compared to the energy supplied for this process. In addition, the quantity of CO_2 emitted during the desalination process is about 13 Mt. of CO_2 (Chandrasekharam et al. 2015c).

Table 3 Main aquifers supplying water to Saudi Arabia (modified after UN-ESCAW 2013, Powers et al. 1966)

Aquifer	Capacity MCM	Proven reserves MCM	Area km2	Avg. thickness m	Sharing countries	
Saq Ram Sst	258,400	103,360	300,000	800	Jordan, Saudi Arabia	Cambrian to lower Ordovician
Wajid Sst	237,500	95,000	170,000	550	Saudi Arabia, Yemen	Permian
Tawila (Tabuk)	109,800	43,920	142,000	775	Saudi Arabia, Yemen	Devonian
Jawf Lst Sst	74,000	38,480	85,000	400		Devonian
Minjur Sst	171,300	111,340	48,000	400		Triassic
Wasia/Biyadh/ Sakha Sst	66,600	33,300		600	Iraq, Saudi Arabia	Cretaceous
Umm er Raduma Lst	6000	3000		500	Bahrain,Qatar, Saudi Aabia, Kuwai, Oman	Eocene

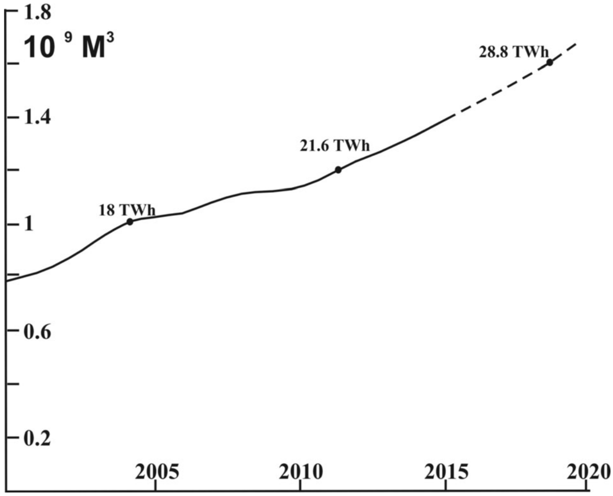

Fig. 2 Current and projected desalination process to get fresh water using fossil fuels and the electricity generated during this process (modified after Chandrasekharam et al. 2015c)

Currently 33 desalination plants are in operation in Saudi Arabia. With government's subsidy, the cost of desalinated water is 0.03 US$/m^3 which is far less than the average cost of US$ 6/m^3 that is being charged by countries across the world (Taleb and Sharples 2011, Chandrasekharam et al. 2015c). Besides domestic and agricultural irrigation purposes, water is also required for energy production. The world energy sector consumed about 583 billion cubic meters of water in 2010 and by 2030 cmption will increase by 85 % (IEA 2012). Demand is directly linked to population growth and the need to increase economic growth through industrial activities (IEA 2012). The most significant water consumers in the power sector are fossil fuel and nuclear powered plants. Water is required to irrigate crops to support biofuels based power plants. Solar photo voltaic (solar pv) plants need water to clean the panels to maintain output and efficiency in countries like Saudi Arabia (Segar 2014). Solar pv desalination plants operate at 20 % efficiency and can generate 5000 cm^3 / day of fresh water (Ahmad and Ramana 2014). The water requirement of geothermal power plants are low and these power plants can generate fresh water for consumption as well to support industrial and agricultural activities. For countries like Saudi Arabia the most efficient and cost effective method to obtain fresh water through desalination process is to adopt technology based on solar or geothermal energy sources (Ghaffour et al. 2014). As discussed below, solar pv is not cost effective and needs supporting facilities while geothermal can supply baseload power and does not require back-up power (like batteries) and the system can work at >90 % efficiency all the year. The most important support system that water resources can give to the country is in agricultural sector. The country needs water for agricultural activities, especially for growing food like wheat and barley. Wheat is an important item in the Saudi food diet, consumed commonly in the form of pita. Average per-capita consumption is 241 g per day or 88 kg annually. The total wheat consumption in Saudi Arabia in MY 2013–2014 was 3.25 million metric tones. Due to the new government policy, wheat imports are expected to reach 3.03 million metric tones in MY 2013–2014 compared to 1.92 million metric tones in 2012–2013 (USDA 2013). Due to water stressed situation the country has adopted a policy to phase out the production of wheat from 2016. This is an alarming situation that the country has not realized. Any country's food security has to be with the country and cannot be outsourced. However, such water stressed situation can be mitigated through developing its geothermal resources to support desalination process and to supply fresh water for the domestic as well as for agricultural sectors.

3 Geothermal Resources Potential of Saudi Arabia

Due environmental issues related to emission of large volume of greenhouse gases (CO_2 and methane) (IPCC 2007), stress on fresh water availability and decline in agricultural produce, the country has now taken initiative to promote renewable energy resources to reduce dependency on fossil fuels in domestic sector and to increase its GDP by exporting the domestic consumption of 3 billion barrels of oil. This initiative is an essential step towards a healthy and sustained energy and food security development and to cultivate clean development mechanism (CDM) and reduce CO_2 emission (Chandarasekharam et al. 2014a, b, 2015c). The western Saudi Arabian shield hosts two distinct geothermal systems: the hydrothermal systems represented by hot springs and the Enhanced Geothermal Systems (EGS) represented by radiogenic granites that generate high heat due to the high concentration of uranium, thorium and potassium (Fig. 3).

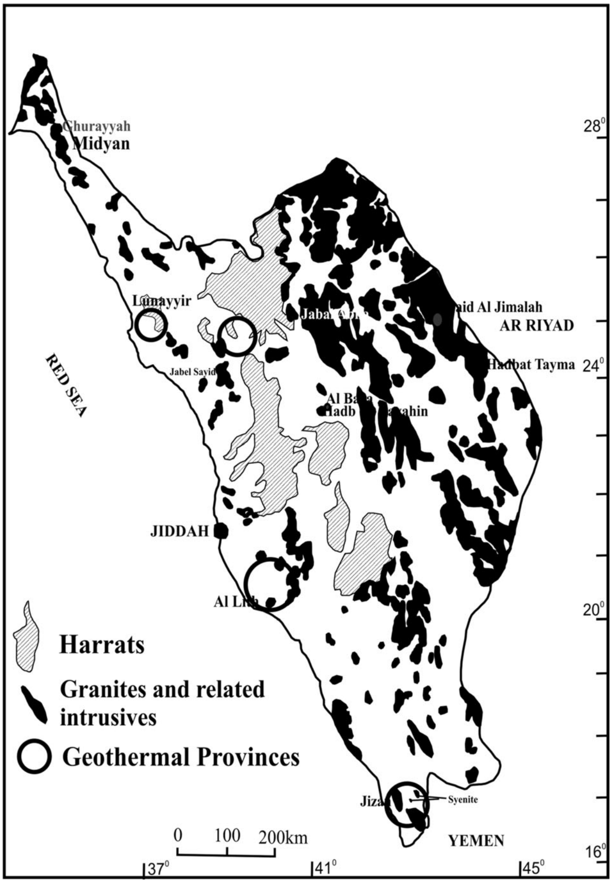

Fig. 3 Arabian shield showing the locations of geothermal provinces, harrats and granites (modified after Chandarasekharam et al. 2014a)

3.1 Evolution of the Hydrothermal Systems

The evolution of hydrothermal systems is related to the Harrats or the volcanic fields that resulted due to the opening of the Red Sea rift between 30 and 5 Ma. The volcanic activity continues till today as evident from the recent earthquake swarm below Harrat Lunayyir (Fig. 3) (Pallister et al. 2010, Al-Shanti and Mitchell 1976, Duncan and Al-Amri 2013, Koulakov et al. 2015). The Red Sea rift has triggered several regional faults around the Red Sea as well as around the regions of the Persian gulf (Beyhan and Keskinsezer 2016) The area occupied by the volcanic flows is 90,000 sq. km^2 (Coleman et al. 1983). These harrats covered a large part of the paleo-channels along the west coast giving rise to hot aquifers below the harrats. Steam from the host aquifers and steam from the hot lavas resulted in the occurrence of fumaroles at several places within harrats along the western margin. The geothermal gradient recorded in the harrats is >90 °C/km (Coleman et al. 1983). Although bore hole date from oil wells are not available, the subsurface temperatures along the western Arabian shield can be inferred from the oil wells located on either side of the Gulf of Suez. The geothermal gradients recorded around the Hammam Faraun thermal province is >50 °C/km with heat flow value of 95 mW/m^2. The bottom hole temperatures recorded from dry wells varies from 120 to 260 °C (Morgan et al. 1976; Zaher et al. 2011, 2012). Such values are commonly recorded along the entire western Arabian shield geothermal provinces due to, besides magmatic and tectonics activities, under plating of oceanic crust below thinned continental segment and attenuated crust like that observed below Al Lith and Jizan geothermal provinces (110–209 mW/m^2, Gettings et al. 1986, Lashin and Al Arifi 2012, Chandrasekharam et al. 2015a, b Jizan and EGS). The reservoir temperatures estimated in selected sites along the western Arabian shield are >200 °C (Lashin et al. 2014, Chandrasekharam et al. 2015a). Occurrence of such high temperature geothermal systems are common over the land masses around the Red Sea, like Ethiopia, Eritrea Yemen and Egypt, (Chandarasekharam et al. 2014a, b). Kenya which is part of the Afar rift system related to the Red Sea opening, is generating 500 MWe from Olkaria geothermal field. Similarly, the Tendaho geothermal field in Ethiopia, will soon be generating 5 MWe from its pilot geothermal power plant. Bodvarsson et al. (1987) based on the field and power production assessment from the wells drilled in Kenya estimated that the power generation capacity of 1 km^2 of harrats is about 173 x 10^6 kWh. In the case of Saudi Arabia, assuming that about 10 % of energy is extractable from the 90,000 km^2 of the harrats, an amount of 200 x 10^6 kWh of electric power can be generated from the hydrothermal systems associated with the harrats (Chandarasekharam et al. 2014a). Besides the harrats, there are also hydrothermal systems associated with granites, like those occurring at Al-Lith and Jizan (Chandrasekharam et al. 2015a, Fig. 3). These granites, hosting the geothermal systems, contain high concentration of uranium, thorium and potassium and thus generate high heat of the order of >11 μW/m^3 (Mooney et al. 1985, Gettings et al. 1986) and the heat flow values recorded over such granites is >80 mW/m^2 that is greater than twice the global heat flow value of ~45 mW/m^2 (Rybach 1976).

3.2 Enhanced Geothermal Systems

The Arabian shield experienced plutonic events between 900 and 631 Ma, 680 and 630 Ma and 660 to 610 and younger than 610 Ma. During these periods, felsic plutons were intruded represented by granite, granodiorite, tonalite, diorite, syenite and gabbro (Chandrasekharam et al. 2015c). All these rocks contain high concentration of uranium, thorium and potassium and are highly radiogenic. These rocks occupy an area of about 161,467 sq.km (Fig. 3). The heat generation by these granitic rocks varies from 2 to 134 μW/m^3 (Chandrasekharam et al. 2015c). The granites exposed in and around Midyan registered the highest heat production value of 134 μW/m^3. The power that can be generated from such granites using the established EGS technology is about 120 x 10^6 terawatt hour (Chandrasekharam et al. 2015c).

4 Application of Geothermal Energy for Desalination

Geothermal heat (low enthalpy sources with temperature of ~60 °C) can be used directly for membrane distillation process (MD) while other desalination processes like multi effect distillation (MED), multistage flash (MSF), electro dialysis reversal (EDR) and vapour compression (VC) can be operated using electricity generated from geothermal energy (Bundschuh and Hoinkis 2012). In the case of desalination using hot water from geothermal source, the geothermal water is circulated through a heat exchanger to heat seawater and decrease pressure to vaporise the water in a multi-stage chamber. In advanced technology, to generate large volume of desalinated water, the heated hot water is circulated to heat several chambers containing seawater. This method is known as MED-MSF process of desalination (Goosen et al. 2012, Rodríguez et al. 1996).

In the case of high temperature geothermal systems, where the temperatures of the geothermal fluids exceed 150 °C, electricity can be generated using binary technology that is common in several parts of the world. One of the best examples of desalination of seawater using electricity generated by geothermal source is described by Karytsas et al. (2004). The process is expected to generate 80 m^3/h of drinking water and 470 kWh of electricity. The desalination plant has a dual system to utilize hot water to desalinate sea water using MED-MSF technology and to use electricity generated from the geothermal source to desalinate seawater using other technologies described above. The cost of desalinated water is projected to be 1.5 euro/m^3 of fresh water (Karytsas et al. 2004).

5 Advantages of Geothermal Energy Sources

ARAMCO, the state owned oil exploration and production company is keen in using energy source mix for domestic demand and increase the export quantity of oil and gas to enhance the country's GDP. This vision can be achieved by harnessing the geothermal energy resources that are discussed above. Compared to conventional fossil fuel, geothermal energy is environmentally friendly and has relatively minor impacts on the ecosystem and with careful management such minor impact on the environment can easily be managed (Baba and Armannsson 2006). By harnessing the geothermal resources the country can generate 200 x 10^6 kWh from hydrothermal and 120 x 10^6 terawatt hours (120 x 10^{15} kWh) from EGS systems of carbon free electricity (Chandarasekharam et al. 2014b, 2015c). This amount of power is far greater than the currently used 17 million kWh to generate 275 L/day of fresh water through desalination process. By utilizing geothermal energy about 517 x 10^{16} L/day of fresh water can be generated through desalination. The current consumption of water by domestic and agricultural sectors is 23,640 x 10^9 L/y (Table 2). Thus by using geothermal energy source , Saudi Arabia can become water surplus country in the near future and support other Gulf Countries to sustain domestic and agricultural water demand. The geothermal energy is accessible at any part of the earth (e.g. EGS) and the power plants can work throughout the year supplying baseload electricity with minimum downtime. The geothermal systems are driven by the heat conducted from the interior of the earth and the heat generated by the radioactive elements present in acid magmatic rock. Unlike the total energy of the geomagnetic field that is reported to be declining (Bayanjargal 2015), propagation of heat from the earth's interior will continue for several millions of years from now. All the desalination plants in Saudi Arabia are located along the Red Sea in the western margin and along the Persian Gulf coast along the eastern margin. The infrastructure for desalination plants already exists and only the electricity supply to these plants need to be switched from oil based power plants to geothermal power plants.

6 Discussion

Saudi Arabia's percapita consumption of fresh water (domestic and agricultural sectors) is about 960 m^3/y. Since the country receives scanty rainfall, the aquifers are not adequately recharged and the water demand is supported by fresh water generated through desalination process. Saudi Arabia uses energy intensive conventional desalination process while the world uses reverse osmosis process. The conventional desalination methods consume 12 x 10^9 kWh to generate 1 m^3 of fresh water (Ghaffour et al. 2014). Thus this process emits large amount of CO_2. The cost to generate 20,000 m^3/day of fresh water through vacuum membrane technique, is about US$ 0.53/m^3 while the cost to generate similar volume of through using conventional energy source is US$ 1.22/m^3 (Sarbatly and Chiam 2013). The CO_2 related temperature effect that is currently experienced in Saudi Arabia (Almazroui et al. 2012) has direct impact on the agricultural production, especially with respect to wheat production. If the CO_2 emission trend continues at the current rate, then the wheat production will drastically be reduced (Valizadeh et al. 2014). In addition to the climate, water stress condition that forced the government to change the wheat production policy will increase food security threat to the country. In addition, trace element concentrations in agricultural soils irrigated with treated sewage water has increased considerably relative the concentration of such elements in soils irrigated with normal groundwater and desalinated water. This built up of trace elements concentration in soils in certain parts of the country is deteriorating the soil fertility and thereby reducing the crop production (Al Omron et al. 2012). Thus for domestic and agricultural sectors need, desalinated water can be used and subsidy on the cost of desalinated water can be removed once the desalination process lines using geothermal energy source stabilizes. The current cost of desalinated water, processed through conventional energy source, in Saudi Arabia with subsidy is 0.03 US$/$m^3$ which is far less than the average cost of US$ 6/m^3. This cost is much higher compared to the cost projected by Karytsas et al. (2004) using geothermal energy source. Once fresh water is available at affordable cost (with same cost without subsidy) and with abundant fossil fuel reserves, the Saudi Arabia can have strong control over energy and food security and help other gulf countries and countries surrounding the Red Sea to improve their fresh water demand.

7 Conclusions

Geothermal energy resources will have a large positive impact on the water availability and agricultural production. The country will have complete food and energy security if this green power is developed. Technology is available at affordable cost from geothermal companies cross the world. The cost of fresh water can be further lowered, without subsidy, from the current US$ 0.03/m^3. Among the gulf countries, Saudi Arabia can become the leader in controlling CO_2 emissions and mitigating the impact on climate change and agricultural production. This will enable the country to support food and energy for the growing population for several decades and stop importing food products.

Acknowledgments The authors extend their sincere appreciation to the Deanship of Scientific Research at King Saud University for its funding of this research group No. (PRG-1436-08). The corresponding author thanks the Director Indian Institute of Technology Bombay for providing the facilities for this work.

References

Abderrahman WA (2001) Energy and water in arid developing countries: Saudi Arabia, a case-study. Water Resources Develop 17:247–255

Ahmad A, Ramana MV (2014) Too costly to matter: economics of nuclear power for Saudi Arabia. Energy 69:682–694

Al Omron AM, El Maghraby SE, Nadeem MEA, El Eter AM, Al Mohani H (2012) Long term effect of irrigation with the treated sewage effluent on some soil properties of Al-Hassa governorate. Saudi Arabia J Saudi Soc Agri Sci 11:15–18

Almazroui M, Islam MN, Athar H, Jones PD, Rahman MA (2012) Recent climate change in the Arabian peninsula: annual rainfall and temperature analysis of Saudi Arabia. Inter J Climatology 32:953–966

Al-Shanti AMS, Mitchell AHG (1976) Late Precambrian subduction and collision in the Al Amar Idsas region, Arabian Shield, Kingdom of Saudi Arabia. Tectonophy 30:T41–T47

Baba A, Armannsson H (2006) Environmental impact of the utilization of geothermal areas. Energy Sources, Part B: Economics, Planning, and Policy 1:267–278

Bayanjargal G (2015) The total energy of geomagnetic field. Geomech. Geophys. Geo-energ. Geo-resour. (2015) 1:29–33. doi:10.1007/s40948-015-0006-y

Beyhan G, Keskinsezer A (2016) Investigation of the gravity data from Fethiye–Burdur fault zone using the Euler deconvolution technique. Geomech Geophys Geo-energ Geo-resour. doi:10.1007/s40948-016-0028-0

Bodvarsson GS, Pruess K, Steffansson V, Bjornsson S, Ojiambo SB (1987) East Olkaria geothermal field, Kenya 2. Predictions of Well Performance and Reservoir Depletion J Geophy Res 92:541–554

Bundschuh, J. and Hoinkis, J. (2012) Renewable energy applications for freshwater production. CRC Press., 282p

Chandarasekharam D, Lashin A, Al Arifi N (2014a) CO_2 mitigation strategy through geothermal energy. Saudi Arabia Renew Sustain Energy Rev 38:154–163

Chandarasekharam D, Lashin A, Al Arifi N (2014b) The potential contribution of geothermal energy to electricity supply in Saudi Arabia. Inter. J. Sustainable Energy 2014b. doi:10.1080/14786451.2014.950966

Chandrasekharam D, Lashin A, Al Arifi N, Al Bassam A, El Alfy M, Ranjith PG, Varun C, Singh HK (2015a) The potential of high heat generating granites as EGS source to generate power and reduce CO_2 emissions, western Arabian shield. Saudi Arabia Jour Afr Earth Sci 112:213–233

Chandrasekharam D, Lashin A, Al Arifi N, Al Bassam A, Ranjith PG, Varun C, Singh HK (2015b) Geothermal energy resources of Jizan. SW Saudi Arabia Jour Afr Earth Sci 109:55–67

Chandrasekharam D, Lashin A, Al Arifi N, Al Bassam A, El Alfy M, Ranjith PG, Varun C, Singh HK (2015c) The potential of high heat generating granites as EGS source to generate power and reduce CO_2 emissions, western Arabian Shield, Saudi Arabia. J African Earth Sci 112:213–233

Coleman RG, Gregory RT, Brown GF (1983) Cenozoic volcanic rocks of Saudi Arabia. USGS Open file report:83–788

Duncan RA, Al-Amri AM (2013) Timing and composition of volcanic activity at Harrat Lunayyir, western Saudi Arabia. J Volcanol Geotherm Res 260:103–116

ESCWA (2001b) The role of desalinated water in augmentation of the water supply in selected ESCWA member countries. United Nations, New York

FAO (2008) Irrigation in the Middle East region in figures: AQUASTAT survey-2008, FAO water reports. Food and Agriculture Organization of the United Nations, Rome, 423 p

FAO (2009) Groundwater management in Saudi Arabia, draft synthesis report , 14pFood and Agricultural Organization

Gettings ME, Blank HR, Mooney WD, Healey JH (1986) Crustal structure of southwestern Saudi Arabia. J Geophy Res 91:6491–6512

Ghaffour N, Lattemann S, Missimer T, Ng KC, Sinha S, Amy G (2014) Renewable energy-driven innovative energy-efficient desalination technologies. App. Energy 136:1155–1165

Goosen, M., Mahmoudi, H. and Ghaffour, N. (2012) Overview of renewable energy technology for freshwater production, in J. Bundschuh and J. Hoinkis (Eds) "Renewable energy applications for freshwater production. CRC Press., 54–106

IEA. (2012) International Energy Agency: Water for Energy: Is Energy becoming thirstier resource? 2012; 33

IPCC (2007) Summary for policymakers. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution ofWorking Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdomand New York, NY, USA

Kajenthira A, Siddiqi A, Anadon LD (2012) A new case for promoting wastewater reuse in Saudi Arabia: bringing energy into the water eq. J Environ Management 102:184–192

Karytsas C, Mendrinosa D, Radoglou G (2004) The current geothermal exploration and development of the geothermal field of Milos island in Greece. *GHC Bull* 25:17–21

Koulakov I, Khrepy SE, Al Arifi N, Kuznetsov P, Kasatkina E (2015) Structural cause of a missed eruption in the Harrat Lunayyir basaltic field (Saudi Arabia) in 2009. Geology 43:395–398

Lashin A, Al Arifi N (2012) The geothermal potential of Jizan area, southwestern parts of Saudi Arabia. Inter J Phy Sci 74:664–675

Lashin A, Chandrasekharam D, Al Arifi N, Al Basam A, Chandrasekhar V (2014) Geothermal energy resources of wadi Al-Lith, Saudi Arabia. J African Earth Sci 97:357–367

Lovelle, M. (2015) Food and water security in the Kingdom of Saudi Arabia. Strategic paper, Future Directions International Pvt. Ltd., Australia (www.futuredirections.org.au accessed on 9 Oct 2015) 8p

Mooney WD, Gettings ME, Blank HR, Healy JH (1985) Saudi Arabian seismic refraction profile: a travel time interpretation of crustal and upper mantle structure. Tectonophy 111:173–246

Morgan P, Blackwell DD, Fanis TG, Boulos FK, Salib PG (1976) Preliminary temperature gradient and heat flow values for northern Egypt and the Gulf of Suez from oil well data in. Geotherm Energy 1: 424–438

Pallister JS, McCausland WA, Jonsson S, Lu Z, Zaharan HM, El Hadidy S, Aburukbah A, Stewart ICF, Lundgren PR, White RA, Moufti MRH (2010) Broad accommodation of rift related extension recorded by dyke intrusion in Saudi Arabia. Nature Geoscience 3:707–712. doi:10.1038/ngeo966

Powers, R.W., Ramirez, L.F., Redmond, C.D. and Elberg, Jr. E.L. (1966) Geology of the Arabian Peninsula Sedimentary Geology of Saudi Arabia. USGS Professional paper 560D, 154p

Rodríguez, G., Rodríguez, M., Perez, J. & Veza, J. (1996) A systematic approach to desalination powered by solar, wind and geothermal energy sources, In: Proceedings of the Mediterranean conference on renewableenergy sources for water production. European Commission, EURORED Network, CRES, EDS, 10–12June 1996. Santorini, Greece, pp. 20–25

Rybach, L., (1976) Radioactive Heat Production: A Physical Property Determined by the Chemistry *in* R.G.I Strens (Etd) "The Physical and Chemistry of Minerals and Rocks". Wiley-Interscience ublication, New York, 245–276

SAMA (2010) Forty sixth annual report: the latest economic developments 1431H (2010G). Research and Statistics Department, Riyadh, Saudi Arabian Monetary Agency

Sarbatly R, Chiam CK (2013) 2013. Evaluation of geothermal energy in desalination by vacuum membrane distillation. App. Energy 112:737–746

Segar C (2014) Renewable augment gas Saudi energy mix. J IEA 7:40–41

Taleb HM, Sharples S (2011) Developing sustainable residential building in Saudi Arabia: a case study. App Energy 88:383–391

UN-ESCAW (2013) Inventory of Shared water resources in western Asia. United Nations Economic and Social commission for western Asia (UN-ESCAW) and Federal Institute for Geosciences and Natural Resources report. UN, NY. 626p

USDA, (2013) Global Agricultural Information Network and Feed annual: Saudi Arabia, USDA foreign agricultural service report SA. 1302:18

Valizadeh J, Ziaei SM, Mazloumzadeh SM (2014) Assessing climate change impacts on wheat production (a case study). J Saudi Soc Agri Sci 13:107–115

Zaher AM, Saibi H, Ehara S (2012) Geochemical and stable isotopic studies of Gulf of Suez's hot springs, Egypt. Chinese J Geochem 31:120–127

Zaher MA, Saibi H, El-Nouby M, Ghamry E, Ehara S (2011) A preliminary regional geothermal assessment of the Gulf of Suez, Egypt. J African Earth Sci 60:117–132