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REVIEW

Groundwater availability and water demand sustainability over the upper mega aquifers of Arabian Peninsula and west region of Iraq

Salih Muhammad Awadh[1] · **Heba Al-Mimar**[1] · **Zaher Mundher Yaseen**[2]

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Abstract

The current research is devoted to highlight the past, present and future status of groundwater characteristics over the Arabian Peninsula (AP) and west region of Iraq. The Umm er Radhuma, Rus Dammam and Neogene deposits are the major hydrostratigraphic units supplying the main groundwater resources in the AP. Water shortage is still a major problem for many countries in the world, including oil-producing countries such as Iraq, Saudi Arabia (SA), the United Arab Emirates (UAE), Qatar, Oman and Bahrain. The withdrawal of groundwater has been reflected in salinization of agricultural soils, leading to an increase in high-cost technologies such as desalination of seawater to provide suitable water for diverse sectors. Hence, the use of seawater desalination as a major source of water is unavoidable, and country development requires the use of renewable energy as protection of the environment. The need to conserve and use groundwater resources efficiently is highly essential owing to the fact that it is the only natural source of water in such developing countries of global importance. The review comprises various essential components related to groundwater variability including the hydrogeological aspects, climate change, drawdown and abstraction, rainwater harvesting, desertification and population increment. Based on the reviewed perspectives, various practical visions are discussed for better groundwater management and sustainability. This research is presented as a milestone for diverse future works and investigation that might be conducted for better water resources management over the AP region.

Keywords Groundwater management and sustainability · Groundwater quality · Desertification · Rainwater harvesting · Climate change

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✉ Zaher Mundher Yaseen
yaseen@tdtu.edu.vn

Salih Muhammad Awadh
salihauad2000@yahoo.com

Heba Al-Mimar
dr.almimar@yahoo.com

[1] Department of Geology, College of Science, University of Baghdad, Baghdad, Iraq

[2] Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

1 Introduction

This review paper highlights the characteristics of groundwater and the nature of the main aquifers (Umm er Radhuma, Rus, Dammam and Tertiary) in the Arabian Peninsula (AP) and the impact of climate change on the future of water in the Arabian Gulf countries and Iraq. The study area is located on the Arabian platform including the eastern and southern parts of SA, The UAE, Kuwait, Bahrain, Qatar, Oman and the western part of Iraq (Fig. 1). The availability of water resources in the AP is limited and characterizes by scarcity (Rijsberman 2006) induced by semi-arid to hyper-arid climates (Scanlon et al. 2006). About 1.3 million live in Western Desert of Iraq (Shubber 2009), which covers approximately 32% of whole Iraq (437,072 km^2) characterized by hyper-arid climate (Middleton and Thomas 1992).

Most populations in the Gulf states and Iraq depend on mainly fossil groundwater reserves, which are predominantly stored in the sedimentary formations of the Arabian Platform (Schulz 2017). Population growth is growing rapidly with the high rate of arrival of migrant workers from other Arab countries, Pakistan, India and Europe up to 8 and 10% per annum, increasing the demand for water (Pike 1985). Interstate aquifers are an interesting subject. The main water storage in the AP is located on the Arabian platform within formations of the Tertiary age. The Tertiary aquifer systems on the Arabian platform have been investigated by many researchers; for examples Al-Ibrahim (1991), Bakiewicz et al. (1982), Beaumont (1977) and Pike (1985) studied the development of water resources and water balance of the main giant aquifers in the AP; Dirks et al. (2018) and ESCWA and BGR (2013) focused on hydrological aspects of the Umm er Radhuma aquifer in the AP, while Al-Fatlawi 2010a, b focused on the Umm er Radhuma aquifer in the

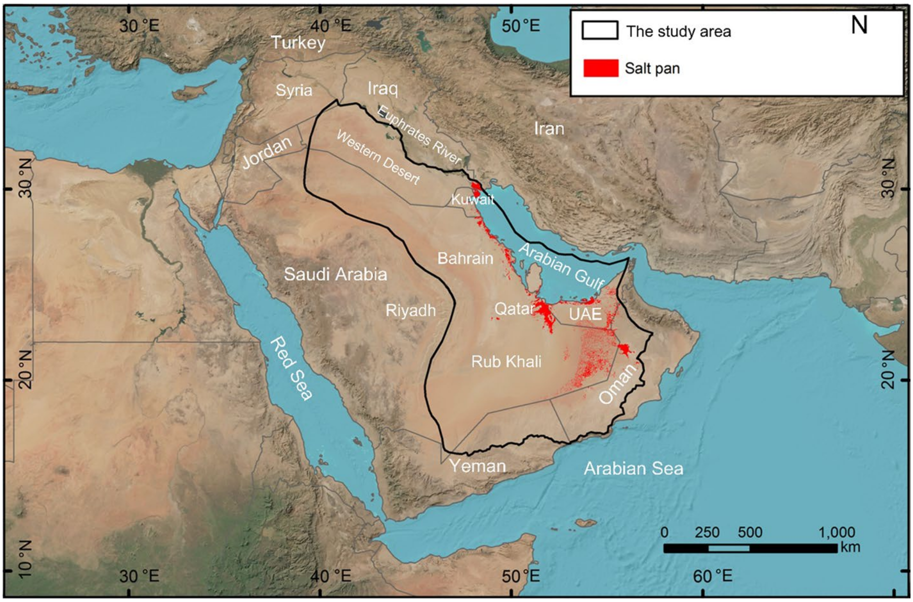

Fig. 1 Location map shows the study area within the Arabian Peninsula, a part of west of Asia (Schulz 2017)

western Iraq only in terms of geological and hydrogeological characteristics. The shared aquifers extension in the whole countries in the AP was also investigated by the Food and Agriculture Organization (FAO 1980). Water is typically experiencing extreme evaporation in the arid climates with the extreme temperature (Raghavendra and Deka 2015; Sayl et al. 2016). Evaporation in the lands of dry climate forms salt pans as a sign of significant water loss from the groundwater aquifers (Ghorbani et al. 2017; Qutbudin et al. 2019; Salih et al. 2019). Groundwater is no longer sufficient to cover the high demand for irrigating the agricultural lands, so desalination is an inevitable option, especially with regard to water supply to the population (Margat and Van der Gun 2013). The subject of groundwater in arid lands is still widely a significant issue. The main challenge is the growing discrepancy between demand and supply of water; in particular, the AP is the driest parts of the world (Odhiambo 2016). The importance of the studied groundwater availability problem is not restricted on the AP region; however, it has received much attention on the global level. Recently, there have been several studies conducted on the groundwater sustainability and development. Kalhor and Emaminejad (2019) studied the influence of the groundwater availability on the cities urbanization of Georgia and USA using the application of remote sensing. Awad (2019) evaluated the deterioration of groundwater at Egypt considering the hydrogeological and hydrochemical aspects. Risk assessment of heavy metals of groundwater resources on human and irrigation system consumptions was conducted by Lanjwani et al. (2019). Bedaso et al. (2019) assessed the groundwater sustainability under climate change using isotopic tracers and climate model for Ohio state, USA. Numerous other studies established on the perspective of understanding the influence of groundwater availability of multiple hydrological and environmental aspects (Ali and Abdel-Hameed 2018; Das and Pal 2019; Niaz et al. 2018; Pande et al. 2019).

The significance of the current review is to provide a comprehensive vision on the water resources (i.e., groundwater) under the influence of climate changes. The countries of the area of interest suffer mainly from water scarcity, and the coming fourth year will be more severe in terms of amount of groundwater and global warming. So, water consumption much higher than rainfall was basically predicted. The objectives of the current review paper are: (1) to provide a comprehensive vision of the water resources (i.e., groundwater) under the influence of climate changes and (2) alert a sharp decline in water table and decreasing recharge dramatically.

2 Simplified geological and stratigraphic overview

The AP is divided into the Arabian Shield and the Arabian Platform. The Arabian Platform includes the upper mega aquifers that form an important part of the sedimentary column of Lower Cretaceous to the Neogene age. The altitude of this succession varies from about 500 m a.s.l. in the vicinity of outcrops in the west to about 4000 m b.s.l. in the east (Schulz 2017). The study area was affected by orogeny movements that led to miss part of sedimentary succession forming unconformities (Kalbus et al. 2011) and tilting of beds that influence the flow direction of the groundwater. The generalized exposures with their ages are shown in Fig. 2, whereas the aquifers in the sedimentary succession from the Cretaceous to the Tertiary are displayed in Fig. 3.

In the AP, the non-renewable groundwater is mainly sourced from the sedimentary and deep rock aquifers which serve as a reservoir of the “fossil” water formed over 1000 to 32,000 years ago (Chowdhury and Al-Zahrani 2015). Paleohydrological

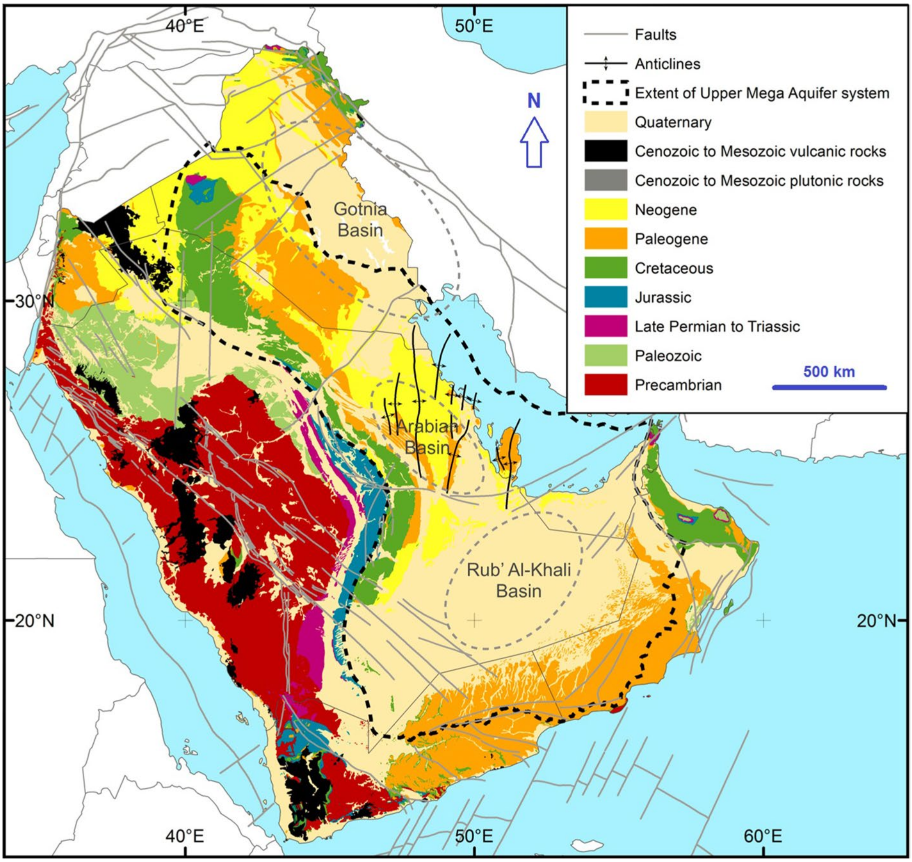

Fig. 2 Geological map of the Arabian Peninsula, after USGS and ARAMCO (1963) and (Baniasad et al. 2016)

evidence has suggested that groundwater recharge does occur sometimes during the Late Pleistocene glaciation or during the Early Holocene period when climates were at least 5 °C cooler and wetter. However, the failure of recharging the total groundwater storage nowadays made the fossil aquifers to be considered "storage-dominated rather than recharge-flux-dominated" (Taylor et al. 2013). The decline of the groundwater levels can be attributed to the pumping out of more water than can be naturally replaced by recharges. Another factor implicated is low natural recharge rates due to climate changes even though climate changes do affect the flow of groundwater into shallow aquifers (Bates et al. 2008; Raghavendra and Deka 2016). The geological setup of any location has been established to influence the groundwater distribution and occurrence pattern of the area (Krishnamurthy and Srinivas 1995). The Quaternary wadi fills in the AP are structurally controlled, with sheet wash from the plateau area being the material. The streams of the watershed are composed mainly of alluvial, serving as a prospective site for groundwater development. Also lining the stream channels are eroded pediplains which line the high- and low-lying areas. There are also lateral formations along the highly fractured, weathered and dissected plateau

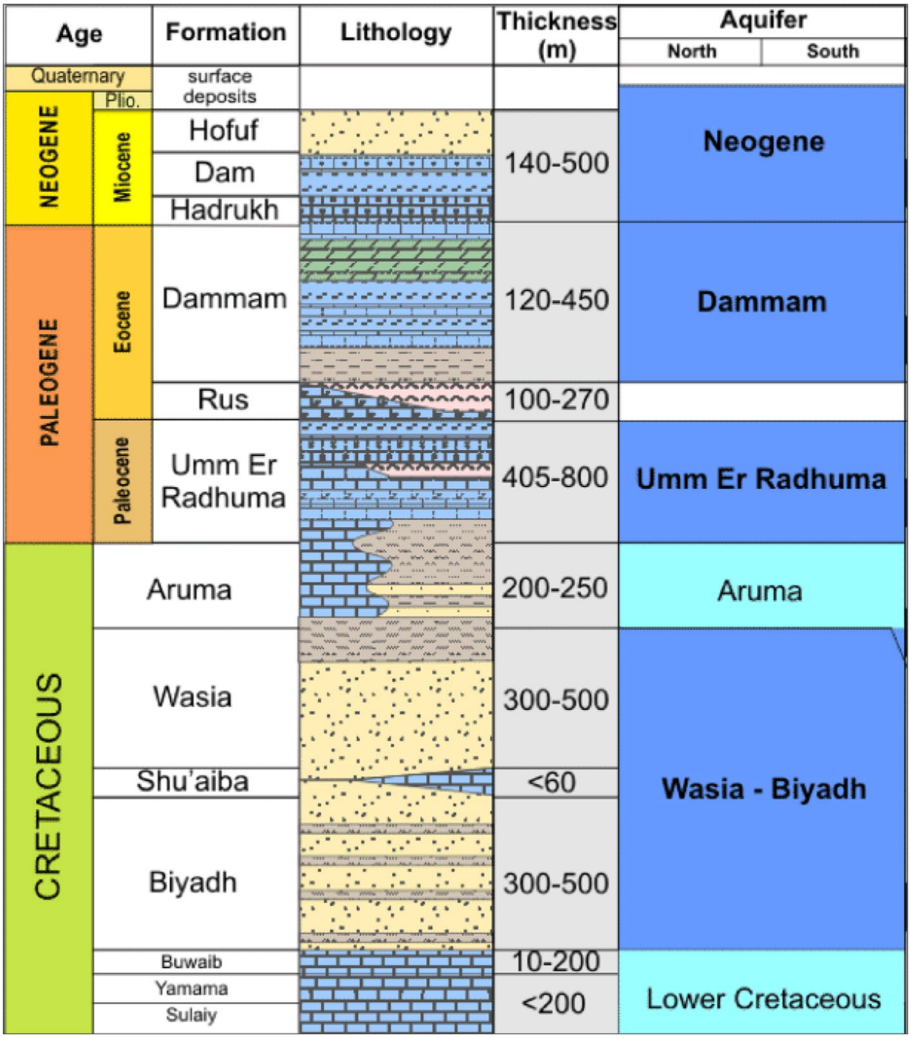

Fig. 3 Typical stratigraphic column displays the Cretaceous and Tertiary aquifers on the Arabian platform in the Arabian Peninsula (Sharland et al. 2001)

units, covering a significant portion of the wadis. The notable features of pediments are often low permeability, high elevations, poor infiltration rate, being around the dissected regions of the plateau, as well as irregularly sized and shaped water divide areas (Al-Sayari and Zötl 1978). Tertiary basalt flows are noticed in the western regions of the AP; they cover the wadis and bury the channels. Their formation is due to the thick overburden of weathered materials on the coalescence of buried pediments. They are highly porous and permeable and characterized by a high infiltration rate. They have a good-to-moderate groundwater prospect.

3 Hydrogeological setting

The hydrostratigraphic succession in the study area consists of different formations belonging to ages range from the Lower Cretaceous to the Neogene (see Fig. 3). The E–W profile of aquifer stratigraphy along 705 km that had been conducted by Scanlon et al. (2006) is displayed in Fig. 4. The Umm er Radhuma Formation (mainly carbonates) and the overlying the Rus (mainly gypsum and anhydrite), Dammam (mainly carbonates) and Neogene (mainly marly limestones) are common mega aquifers that form the main hydrogeological system in the neighboring countries in the study area (Pike 1985). The Umm Er Radhuma Aquifer karstified limestones dipping gently eastward of about 0.1° and finalized to be bounded by the Euphrates River (Dirks et al. 2018). It has thickness of 250 m in SA, thinning in the north part of the Western Desert of Iraq to reach 50 m, but thickening in the south part of the Western Desert of Iraq to be 500 m, in Kuwait 650 m, in Qatar 370 m, in the UAE 370 m and in the Oman up to 650 m (Nairn and Alsharhan 1997).

In Iraq, Umm er Radhuma aquifer has variable thickness ranging from 30 m to 500 m; it unconformably overlies the Tayarat formation and underlies the Dammam formation (Buday 1980). This formation is divided into Lower member (M. Paleocene) and Upper member (U. Paleocene) (Sissakian and Mohammed 2007). It consists of two aquifers: unconfined aquifer covering an area of 60,068 km^2 and confined aquifer covering an area of 91,766 km^2. It is almost located in the northern part of the Western Desert of Iraq with eastward general flow and covers most parts of the southern part of the Western Desert of Iraq with a general flow toward northeast (Al-Basrawi and Al-Jiburi 2009). This heterogeneous formation is characterized by the secondary permeability represented by fractures, karst, cavities, open shafts and sinkholes (Idrotechneco 1977), so its transmissivity being of high variation varies from 3 to 2100 m^2/day (Al-Fatlawi 2010a, b). Aquifers contain a fossil water due to long residence time, where its resident more than 20,000 years in the Umm Er Radhuma aquifer was based on 14C dating measured in Al-Hufuf (Wagner et al. 1999). The geometry of the Umm Er Radhuma with the generalized isopach map is presented in Fig. 5. The Umm er Radhuma-Dammam formations form aquifer systems of about 2200 km from the north of Iraq to the southern border of the AP covering an area of about 1,220,000 km^2, of which 363,000 km^2 is covered by outcrops. The most area of these systems is emplaced within SA, which share the northern, eastern and southern parts

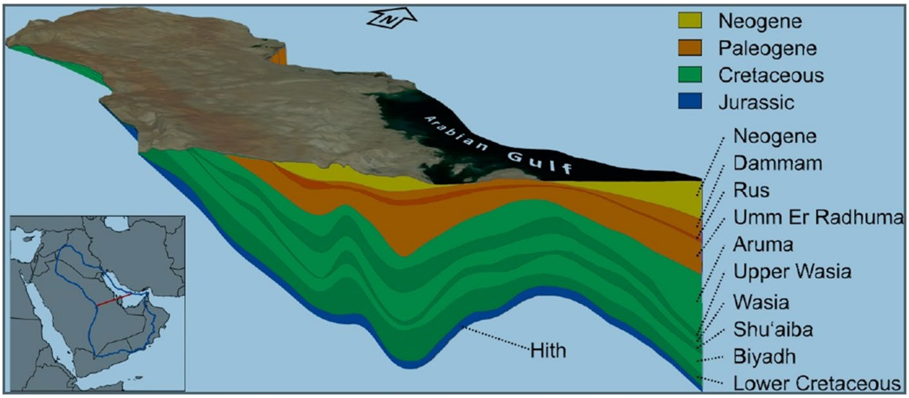

Fig. 4 Cross section with 705 km long displaying the aquifer stratigraphy (Scanlon et al. 2006)

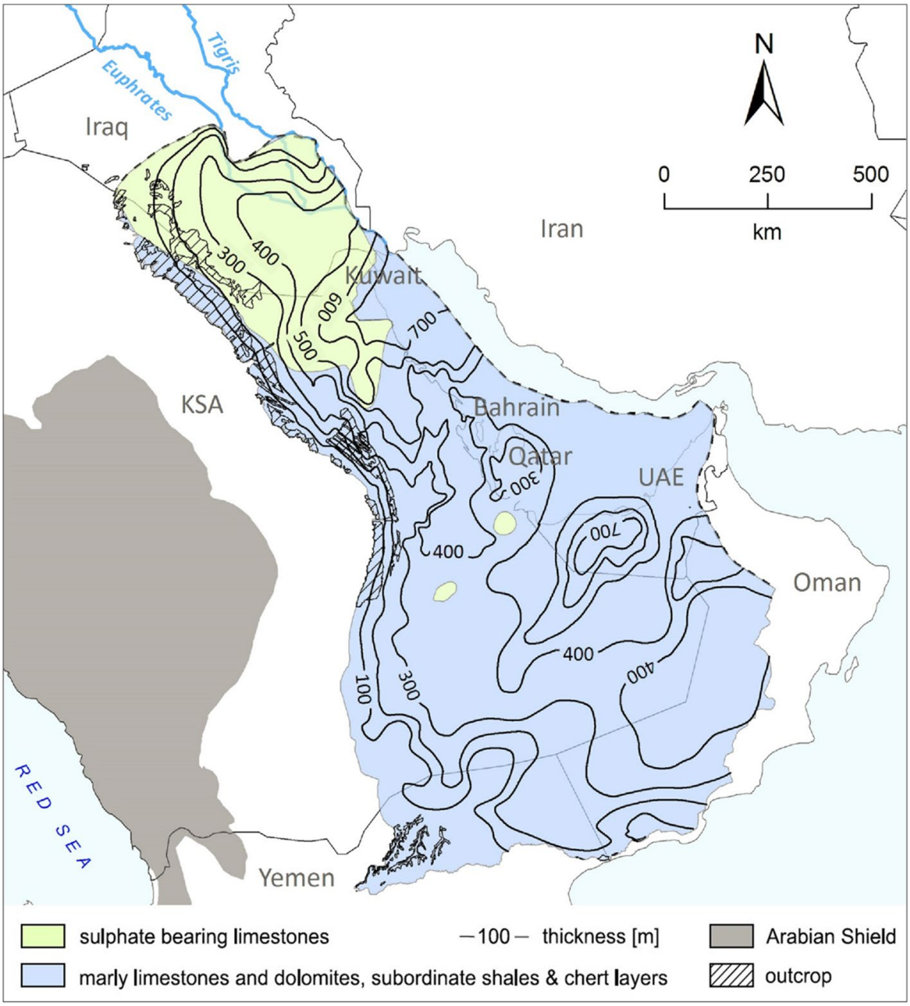

Fig. 5 Geometry and litho-isopach of the Umm Er Radhuma Formation in the Arabian Peninsula (Dirks et al. 2018)

with neighboring countries with 662,000 km^2 (UN-ESCWA 2013). It is a large aquifer in the arid regions in which inflows almost equal outflows (Dirks et al. 2018). The thickness of Rus aquitard in the eastern part of SA is about 50 m, increases to 80 m toward Kuwait, 100 m in the southwest of Iraq, 100 m in UAE and 130 m in Oman (Nairn and Alsharhan 1997). The sulfate Rus in the northern Qatar and east of the Rub' Al-Khali changes to no sulfates, forming an upward extension of the Umm Er Radhuma aquifer (Dirks et al. 2018). The porous limestone of Dammam aquifer has a thickness of about 30 m and changes eastward to reach 120 m in southwest Kuwait, 230 m in UAE, 250 m in Iraq and 250 m in Oman. Groundwater of the Dammam aquifer in Iraq is characterized slightly brackish dominated by sodium and sulfates (Awadh et al. 2016). The Neogene aquifer has thickness eastward up to about 650 m in Kuwait and 900 m in the UAE (Nairn and Alsharhan 1997). The salt pans are located close to shoreline of the Arabian Gulf and in the desert of the

Rub Khali formed by the capillary action in arid climate. These salt pans are fed from shallow groundwater, which cover a total area of 33,000 km^2 (Schulz 2017). These hydrostratigraphic units are covered by Quaternary sediments forming from sandy soil, gypsiferous soil and sabkha. The general nature of these aquifers varies between confined aquifers in areas where seal strata separate the formations, while they change to unconfined aquifers in places where there are a lot of karsts and fractures resulting from dissolution or tectonics. The groundwater in these aquifers flows from the southeastern SA toward the Euphrates basin in Mesopotamia at the north, while it moves from western of the SA toward the Western Desert of Iraq to the east. These aquifers are mostly located beneath arid desert lands, most of which are in SA, represented by the Rub Al-Khali, and in Iraq represented by the Western Desert that is adjacent to SA from the east.

4 Groundwater quality

At the aquifer exposures, a clear effect of evaporation can be proven by the domination of the sulfate water associated with the presence of gypcrete on the surface. Groundwater in these aquifers is between connate water of ancient ocean and meteoric water penetrated into the aquifers through fractures connecting the surface and the aquifer. Groundwater chemistry is affected by its interaction with the aquifer and by leaching ions during water penetration from recharge areas (Awadh et al. 2016). The water chemistry in carbonate aquifers changes to Na-chloride water, which can be detected under sabkhas. The shallow groundwater in the western Iraq is generally characterized by chemical heterogeneity, as magnesium is predominant due to the dissolution of dolomite (Awadh 2018). The lithology of Rus aquifer is characterized mainly by anhydrite and chalky limestones, so it has low transmissivity varied between 20 and 600 m^2/day and less than that of the lower Umm er Radhuma carbonate aquifer, which has a value of 3000 m^2/day (Pike 1985). As usual, lithology and chemical processes control the factors of the water type. Precambrian salt domes in vicinity of Bahrain (Kent 1970), and evaporation of Lower Fars Formation significantly increases the water salinity (Sharland et al. 2001). In each aquifer, the prevailing ions change depends on the extension and location of the aquifer. At the aquifer outcrops, which are located in the eastern part of AP, Ca-bicarbonate water with TDS varies between 300 and 1000 ppm. Eastward, the hydrochemical facies becomes Ca-sulfate with TDS ranging between 1000 and 4000 ppm and is close to the coastline reaching more than 5000 ppm with the predomination of Na-chloride (Dirks 2007). In the vicinity of Gulf shoreline, particularly near Bahrain, Qatar, and UAE, the salinity reaches up to 250,000 ppm. The aquifers are recharged with freshwater from the recent meteoric water via rainfall. Such process is existed in Paleogene aquifers in Bahrain and Qatar, and in Neogene in Kuwait and Oman. In Bahrain, the Rus-confined aquifer hydraulically connects to the underlying Umm er Radhuma aquifer and changes to be unconfined at the eroded areas with TDS of 1000 ppm of Na–Cl type due to seawater intrusion. At the east of Bahrain, the water type in Dammam aquifer is of 2000 ppm with ion domination of Ca-SO4-Cl. In Qatar, the unconfined aquifer that is formed by Dammam formations feeds meteoric water via the secondary permeability. The groundwater can be obtained at depth varying from 100 to 400 m with a TDS value of 350 ppm but changes to be ranged between 600 to 1800 ppm at the shallower depth. The water table in urban area of Qatar suffers from drawdown due to the rapid urbanization (Al Hajri et al. 1992).

5 Climatic characteristics

The AP and Iraq have an arid climate; in general, it is characterized by a hot summer that lasts for four months or more and a cold winter lasting for three months, while spring and autumn are two transitional seasons almost short. The countries suffer from aridity and water scarcity, leading to drought. Drought is a temporal situation that may occur in a certain climate of low rainfall. It occurs in the hydrological system as a reaction to the scarcity of precipitation and high temperatures, causing low surface and groundwater levels and a decrease in water stocks in dams and lakes. Climate change and global warming lead to increase in the evaporation rate and desertification of land, which eventually leads to a deterioration in the quality of soils and reduction in natural resources. The increase in evaporation rates influences the volume of water. Rainfall is limited to certain months, almost starting in October and ending at the end of May. Winter represents the peak of rainfall, with precipitation exceeding 50% of the total annual rainfall, while the amount of rain falling during autumn and spring is together to about 50% or less. The amount of runoff water depends on the evaporation rate, which mainly depends on the solar radiation, temperature, relative humidity and wind speed. The temperature and drought are increasing steadily, and rising temperatures may cause some areas to become unsustainable in the future, leading to a decline in freshwater availability and the use of groundwater resources at a faster rate than rain can compensate for. The heat will increase the incidence in extreme weather events such as hurricanes. The AP is of low average precipitation (<200 mm/year), high evaporation rate (2–3 m^3/year), low recharge rate of groundwater ($<4\%$ of total annual water used) and no reliable surface water resources (Odhiambo 2016). The AP is one most sensitive area to climate change (Giorgi 2006). The annual precipitation amounts and prevailing wind directions have been described by Kummerow et al. (1998), and it is presented in Fig. 6. The average annual rainfall in the west of Iraq and Qatar varies from 28 to 200 mm, in UAE from 50 to 100 mm and in Rub Khali less than 50 mm. The temperature and relative humidity have been described by Dee et al. (2011) (see Fig. 7). The climate of the western Iraq is similar to the climate of the AP, as it is characterized by the general fluctuation of rainfall during the successive years, and depends on the rate of evaporation that varies depending on the temperature rising. The huge amounts of water are lost due to evaporation, which basically exceeds the rainfall rate. The IPCC report estimates an increase in temperature in the region of up to 2 °C in the next 15–20 years and over 4 °C for the end of the century (IPCC 2007). Figure 8 presents the historical scenario of the evaporation and precipitation from 1975 to 1995 and shows the future prediction of the relationship that will result in more water loss due to increase evaporation and scarcity of rainfall.

It is worth reporting that an increase in the average global temperature from 1.4 to 5.8 °C is expected by the year 2100 as a result of changes in the global climatic processes (Erica DeNicola et al. 2015). However, the proportion and magnitude of this change, especially the precipitation levels, will vary regionally (Sulaiman et al. 2018). The most affected by these changes will be water quality and availability due to the direct relationship between climate changes and the hydrological cycle, especially the role of greenhouse gases in global warming. Among the notable effects of climate change on the hydrological cycle are severe temperature changes, increased precipitation intensity, changes in the quantity and seasonal distribution of precipitation, increased evapotranspiration and reduced soil moisture (DeNicola and Subramaniam 2014). In addition to the effects of these natural changes, human activity (overuse of water or anthropogenic pollution) also contributes to the threat

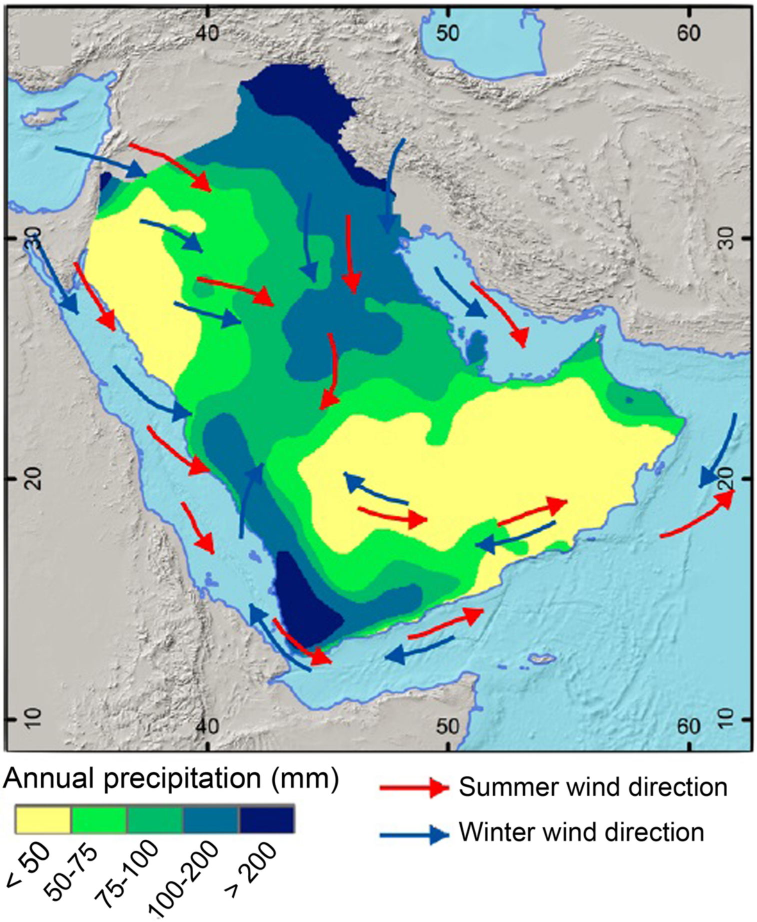

Fig. 6 Average annual precipitation amounts for the period 1990–2010 (Kummerow et al. 1998) and prevailing wind directions (Alsharhan et al. 2001)

on water security in several regions, especially those in the subtropical regions and lower latitude where there are decreases in the total precipitation level, while evapotranspiration and temperatures keep increasing (Khan et al. 2019). These ultimately result in the depletion of potable water resources. Human health is also affected by issues relating to water scarcity since the risk of certain diseases increases with poor water quality and poor sanitation. Acclimatization with climatic changes certainly depends on national resources; hence, the level of suffering associated with climate change is more in the poor and highly populated countries (Sowers et al. 2011). In most of the AP countries, water demands are met through either renewable groundwater and surface water sources, desalinated seawater, treated wastewater, or non-renewable groundwater sources (Chowdhury and Al-Zahrani 2015). In such countries, surface and renewable groundwater are extremely limited due to the lack of permanent surface water and very little rainfall. In the event of rainfall, flooding creates about 16 million cubic feet of run-off per year, which is captured and stored in more than 200 dams across the SA. By 2045, it is estimated that annual rainfall will contribute

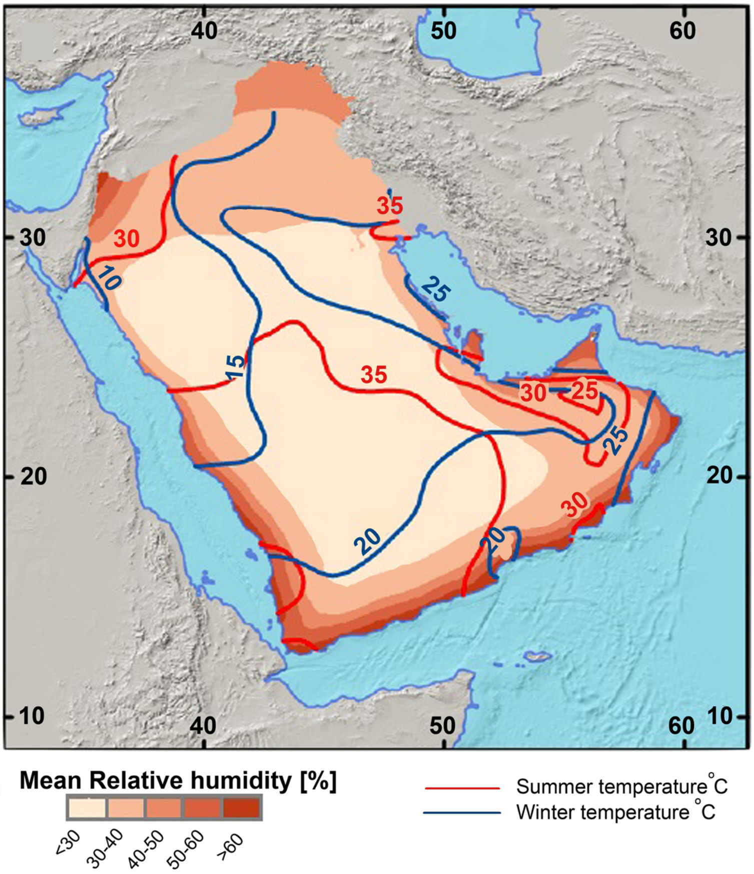

Fig. 7 Mean of temperature and annual relative humidity for the period from 1990 to 2010 (Dee et al. 2011)

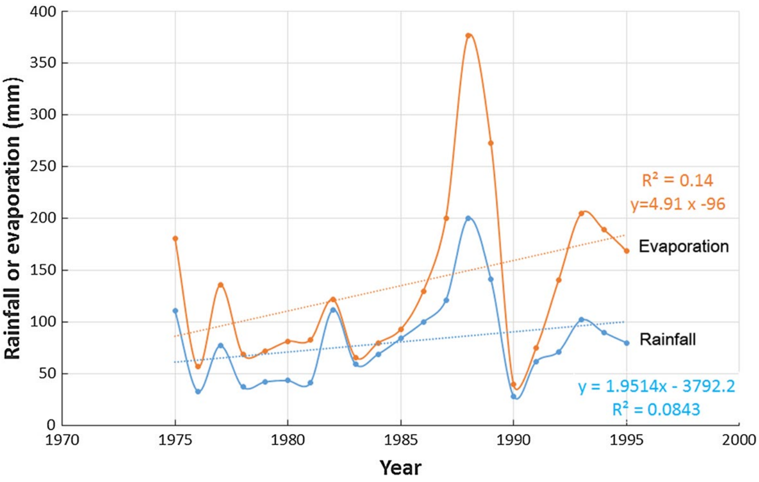

Fig. 8 Rainfall and evaporation prediction in west Iraq

about a million cubic meters of surface water mainly in the west and southwest regions of KSA (Zaharani et al. 2011). The effect of climatic changes will be felt on the unconfined or shallow aquifers, which are involved in the hydrological cycle process in the present time, and as such can serve as suitable geological formations for possible run-off harvesting. Contrarily, the deep and confined aquifers may not be seriously affected by climate changes because they are not in contact with the present-day hydrological cycle; among them are the non-replenishable fossil groundwater storages (Wada and Heinrich 2013). Some conditions such as the sporadic, chaotic, irregular, and complex nature of storm rainfall occurrences, as well as the geological layer composition and geomorphologic features, impact the pattern of groundwater recharge and run-off harvesting (Naganna et al. 2017). Although it is difficult to control, however, it regulates the natural spatial and temporal groundwater recharge. Areas with perennial surface water flow often have incessant infiltration and consequential groundwater recharge, coupled with the seasonal main flow channel, especially during the summer. Arid regions like KSA have available recharge possibilities intermittently due to occasional storm and the associated ephemeral streams in most seasons. In such areas, recharge occurs irregularly and during intense rainfalls, especially during the winter. During the other seasons, only the upper soil layer is wet, and water could not reach the groundwater reservoir. Run-off harvesting, especially in arid regions, enhances groundwater recharge facilities.

6 Groundwater drawdown and abstraction

The Umm Er Radhuma aquifer is a leaky unconfined-to-confined aquifer, while the Rus aquitard, Dammam aquifer and Neogene beds permit for only few leakages, even at high head differences (Dirks et al. 2018). Groundwater is of limited recharge from rainfall due to very limit outcrop. The head loss of groundwater is of 400 m a.s.l. between the outcrops at the southeastern part of the aquifer and sea level at the coastline of the Arabian Gulf. The water table, since 1980 drawdown, is 150 m as it was detected in the Al-Hufuf region (Schulz et al. 2015). The hydraulic gradient of water table is 0.055°. A huge quantity of groundwater seeps to the Arabian Gulf floor (Taniguchi et al. 2002). The springs, the Euphrates River and the Shatt Al-Arab are another different media exhausting high discharge of groundwater from the Umm Er Radhuma and Dammam (Krasny et al. 2006). Largest groundwater quantity is consumed via supplying the water for various purposes; for example, domestic purpose, municipals, irrigation for the agricultural lands, various industries, injection oilfields to enhance the oil production. Currently, outflows from the Umm er Radhuma aquifer are dramatically greater than inflows, largely due to agricultural groundwater abstraction (Dirks et al. 2018). In the SA, more than 80% of the 128 MCM extracted water from the Umm er Radhuma aquifer is used for irrigation purposes, and the rest 20% is for other uses such as municipal, industrial and water livestock (ESCWA and BGR 2013). The renewable freshwater resources per capita [m3a-1] at the country scale for 2015 according to FAO (2016) are 37-500 in the SA, < 37 in each of UAE, Kuwait, Qatar, Bahrain and > 1700 in Iraq. Groundwater abstraction in the SA from the upper mega aquifer system from 1955 to 2010 is presented in Fig. 9. The large portion of water was consumed for agricultural purposes. The countries of the AP consume much more water for agricultural purposes than they consume for other purposes combined, with less consumption in the industrial sector (Fig. 10). The historic demand for water in the AP states for 35 years extending from 1990 to 2025 is represented by million cubic meters in Fig. 11.

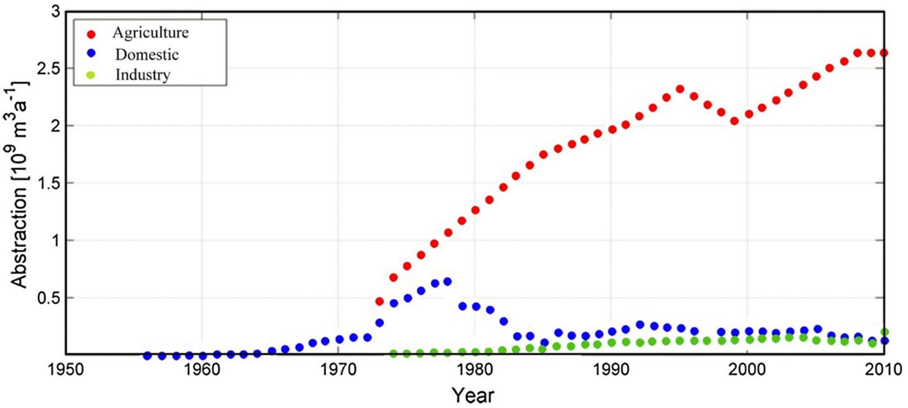

Fig. 9 Groundwater abstraction in Saudi Arabia from the upper mega aquifer system from 1955 to 2010 (Schulz et al. 2015)

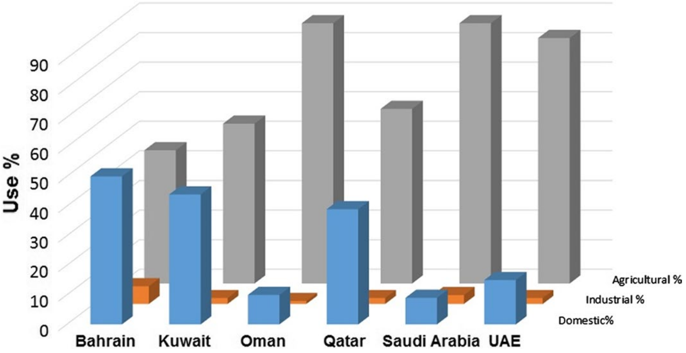

Fig. 10 Freshwater consumption for Arabian Peninsula countries

A positive linear relationship shows a future increase in water demand resulting from rapid population growth. The UAE needs the largest amount of water, followed by SA, Qatar, Kuwait, Bahrain and Oman. The groundwater system is also affected by the mining works; in the study area, many mines and quarries within limestone and sand beds are spread, depleting the amount of groundwater. Apaydın (2012) stated the sand–gravel pits have to be banned immediately; a reclamation project applied and abstraction must be reduced.

7 Groundwater and its relationship with desertification

About one-fifth of the world population is affected by desertification (affecting about 70% of the total drylands (3.6 billion ha) and about one-quarter of the total land area of the world (Tolba 1992). Land susceptibility to desertification is usually due to certain factors like the climate of the area, the state of the soil, water, and natural vegetation; it could also be due to how the natural resources in the area are being explored. The global freshwater reserves are also affected by desertification as it directly affects river flow rates and the

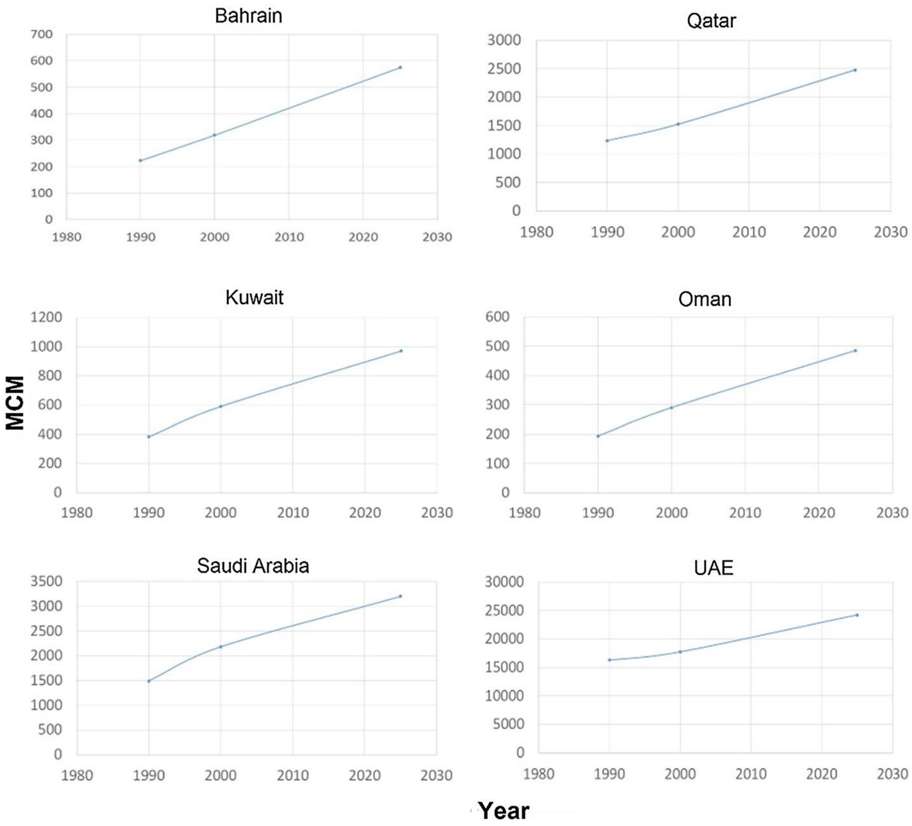

Fig. 11 Historical water demand by million cubic meters (MCM) in Arabian Peninsula countries from 1990 to 2025

level of fresh groundwater. These can result in the silting up of estuaries, salinization, water pollution by suspended particles, and saltwater encroachment into aquifers. The result is a reduction in the biodiversity of both fresh and brackish water fishing catches, increased coastal erosion, interference with the operation of irrigation channels, and adverse effects on human lives. Finally, desertification can accelerate the rate of underground fossil water reserves exploitation, leading to their gradual exhaustion (Koohafkan 1996).

8 The influence of rainwater harvesting on groundwater

The impact of climate changes on different parts of the globe varies as evidenced in the severity of drought in certain regions, while other regions enjoy abundant rainfall over time. In KSA, the annual rainfall and aridity trend have been reported to split most cities in the country into two categories—those that will experience reduced annual rainfall and those that will face increased annual and maximum rainfall (Amin et al. 2013). The rest of the studied cities experience increasing maximum rainfall due to extreme rainfall events that produce flooding. Hence, water shortage in the remote areas of the country can be solved through rainwater harvesting (RWH) whose technology has been in use for several years. This technology allows the storage of rainwater from land surfaces, rooftops or rock catchments into natural or artificial reservoirs. Hence, the RWH system can be used to collect about 60% of the total quantity of run-off from rainfall in the southwestern region of KSA, stored and transported through pipelines to the other parts of the country.

The source of freshwater in most arid and semi-arid areas is groundwater; however, little attention has been given to the potential effects of climate changes on groundwater (IPCC 2007). In the arid and semi-arid areas, aquifers are recharged by floods through fractured and fissured rocks at the possible recharge outcrop areas. They are also recharged from solution cavity limestones or in dolomite, and also through wadis. Engineering structures such as levees, dikes and artificial depression ponds, and successive small-scale groundwater recharge dams can be built at convenient places along the main channel to augment groundwater recharge. Ponds specifically help run-off harvesting after a storm rainfall event, encouraging run-off conservation.

The quality and quantity of water are affected by climate changes and as such has a direct influence on the patterns of water resources management. Groundwater level reflects the level of the balance between its recharge and climate change, and this balance is essential for groundwater storage enhancements. One thing that baffles much is the understanding of the interaction between water and agriculture, and such an interaction can be managed sustainably. Hence, it is necessary to consider the following critical concerns:

(i) Is irrigational water still necessary in this changing climate?
(ii) Can the groundwater recharge locations (natural or artificial) be identified and harvested through RWH?
(iii) Is there any way to manage the various options that ensure a reduced water demand and the water distribution-related risks?
(iv) How can water scarcity risks be appropriately addressed and integrated into land and water management?

Among several elements that should be studied, the quality of the RWH will also be considered as rainwater can be contaminated by several pollutants such as particles, microorganisms, heavy metals and organic substances. Rainwater quality also depends on the catchment area it is collected from; catchment areas can also be contaminated by heavy metals and organic substances as well. Therefore, harvested rainwater must be treated and disinfected through some inexpensive methods like chlorination, slow sand filtration, or pasteurization by solar technology (Helmreich and Horn 2009).

As a matter of fact, water supply is in dire need in the arid and semi-arid regions of the world for several water-related purposes. Most countries are implementing measures to increase their water resource capacity in a bid to be self-reliant and solely dependent on their own water resources. In the arid and semi-arid areas, groundwater storages are the only natural source of water. They have quaternary deposits in wadis as the most appropriate location for groundwater recharges. This is because of the availability of water as run-off which must be stored for future use before losing it to the high evaporation rates of the region. By all indication, the frequency of rainfall occurrence and its magnitude are expected to increase soon; hence, flood and flash flood occurrences are expected to increase proportionally. Therefore, the detailed necessary procedures for RWH have been presented for application in run-off harvesting to an area near Riyadh, SA, in this paper. Hopefully, similar procedures can be helpful in the other regions of the globe for increasing groundwater storage after periods of storm and subsequent run-offs.

Last but not least, RWH is an old method which has recently become useful as a simple adaptation method in the arid and semi-arid regions because of stress, water scarcity and impacts of climate changes. It has been in existence for a long time as a method for rainwater and run-off collection and storage. Run-off harvesting methods are previously used for diverse purposes such as watering, drinking, agriculture and husbandry. They are mainly used in recent years for five major reasons: (1) supporting water stress, (2) reducing effects of water scarcity, (3) providing more cost-effective water supply, (4) improving water quality through artificial mixtures and (5) relieving the influence of climate to a certain level.

9 Population boosting and water scarcity possible solutions

Throughout the history, the unavailability of water in the AP including Saudi Arabia Bahrain, Kuwait, Qatar, Oman, UAE, Yemen in addition to the west Iraq has affected the lives and livelihood of inhabitants (Abdulrazzak 1995; Ukayli and Husain 1988). The accelerated growth of population in combination with increases in per capita water consumption has highly contributed to the increases in water consumption. Throughout 30 years from 1970 to 1990, the population in the countries of the study area has increased almost twofold from 17.8 to 33.5 million. The United Nations (UNs) expected that the population could become 45.5 and 95.6 million, respectively, by the years 2000 and 2025. The situation of the countries of AP in arid and extremely arid regions characterized by limited rainfall, absence of surface water, problems with groundwater salinity, water-quality deterioration, particularly in the coastal areas, resulted in a shortage of water supply. The use of seawater desalination technology and renewable groundwater resources of the low cost have become a necessary requirement for the water supply system in these countries to satisfy the domestic requirements at least.

The limited land and water resources in the AP region have been significantly affected not only by the climate change or other factors, yet the increased rate of population observed in the region (from approximately 77 million in 1950 to almost 288 million in 2000) represents the largest population growth worldwide from 1990 to 1995 (WRI 1999) (see Table 1). Also, the implication of the lifestyle is changed and eating patterns increased the food demand and accelerated the rate of land use in the area due to the aridity of the environment.

Lands have been lost to urbanization due to population growth and other physical changes as well; the per capita share of cultivated land has also been diminished in most

Table 1 The total population of the Arab region countries over (1950–2030) (in 1000)

Countries\years	1950	1960	1970	1980	1990	2000	2010	2020	2030
Iraq	1812	2937	5254	8523	12,987	17,752	24,441	31,483	38,106
Bahrain	74	129	173	279	429	570	677	778	853
Kuwait	90	201	579	1240	2054	1919	2343	2704	2985
Oman	11	20	83	356	1109	2282	3645	5228	7051
Qatar	16	33	89	196	436	554	650	723	757
Saudi Arabia	509	1211	2796	6325	12,602	18,572	26,008	34,252	42,500
UAE	17	36	127	726	1554	2099	2526	2851	3076
Yemen	250	478	842	1660	3350	6886	11,702	18,055	25,969

countries of the Arab region. Lastly, desertification can accelerate the rate of underground fossil water storage exploitation, leading to their gradual exhaustion (Koohafkan 1996).

Most countries of the AP regard freshwater as a limited but precious resource; it is sourced from both renewable and non-renewable sources. Regarding the renewable sources of freshwater, rainfall contributes about 2446 Bcm yr^{-1} and stands as the most renewable source of freshwater in the region. However, most of the water sourced from rainfall is lost to evaporation and/or run-off and as such does not contribute to the regions' wealth. The rate of desertification in this region can be decreased by considering rainwater harvesting, which is yet to be exploited. This effort will require a proper assessment and deployment of appropriate methods, and when properly done, would also decrease wind and water erosion of land.

Arab countries cover 10% of the world's area but receive only 2.1% of its average annual rainfall. Groundwater in the AP countries contributes almost 84% of total water withdrawals. The shortage in rainfall with the rapid population growth has caused dramatic shrinkage in per capita renewable water resources from an average of 2925 m^3/year in 1962 to 1179.6 in 1992 and to an alarming 743.5 in 2011 below the poverty line level of 1000 m^3/year and far below the world average of 7240 m^3/year (IEA 2010). All countries in the AP already face water scarcity, with average water availability per capita below the poverty line. By 2025, Iraq could be with an average above 1000 m^3/year (El-Ashry and Saab 2010). The impacts of climate change by 2030 will resulted in reducing renewable water resources by another 20% as temperatures rises, increasing the frequency of droughts and rising water demand for domestic and irrigation water (Berndes 2008). Groundwater resources in countries of the AP and west Iraq are threatened by pollution and environmental impacts. The overexploitation to meet rising demand for water caused heavy decline on renewable and both of non-renewable groundwater resources. The highest desalination capacity is in the Ap, which is about 81% among the Arab countries. Desalinated water needs to be expanded fivefold by 2025 to cover the population growth. An environmental hazard yielded while using desalination plant, which are powered by the fossil fuel. Wind and wave power are recommended to be used to meet the renewable sources beside the solar energy where the AP and west Iraq have vast solar energy potential. In addition to all the above and to meet the escalating demand, the treatment of the municipal wastewater is strongly recommended.

10 Conclusions

The water demand in the Arab Peninsula region rises as a result of population growth in its countries as it was considered one of the highest in the world. The climate of the region is strongly affected by global climate changes and global warming, and thus, it is suffering from the temperature increment which results in higher evaporation rates that are basically higher than rainfall. The water availability per capita in the study area is accordingly expected to be halved in the future. The outlook for water in the AP and west of Iraq is likely to worsen due to the climate change and current water management policy. Generally, the water storage in the study area is mainly found in Umm er Radhuma, Rus, Dammam and Neogene aquifers that are emplacing on the Arabian platform in the AP. The aquifer systems are in the unsteady state, in which recharge is less than outflow which is largely consumed for irrigation. The un-follow high-technology systems contribute to the waste of large quantities of water. The excessive water consumption is still drawdown the water reserve, leading to desertification. The water table is declining and reaching alarming drawdown values in the Dammam and the Umm er Radhuma aquifers. The sand–gravel pits have to be banned to preserve the groundwater system, and the reclamation project needs to be activated and applied to stop abstraction. The use of drip irrigation and the use of seawater desalination technique for the purpose of drinking, domestic and municipal using alternative energy sources of low cost and reducing the abstractions of groundwater by using dripping irrigation in the desert lands to maintain the water table as steady level at least are therefore recommended.

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Compliance with ethical standards

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References

Abdulrazzak, M. J. (1995). Water supplies versus demand in countries of Arabian Peninsula. *Journal of Water Resources Planning and Management, 121*(3), 227–234.

Al Hajri, M., Shadid, F. T., Al-Hajri, K., & Ahmed, S. (1992). Qualitative and quantitative assessment of drained water from urban ground-water. *Engineering Journal of Qatar University*, *5*, 237–248.

Al-Basrawi, N. H., & Al-Jiburi, H. K. (2009). Hydrogeology of Al-Jazira Area. *Iraqi Bulletin of Geology and Mining, 3,* 71–84.

Al-Fatlawi, A. N. (2010a). *Hydrogeological study for Umm Er Radhuma Aquifer—West of Iraq*. Unpublished Ph.D. thesis, Baghdad University, Baghdad.

Al-Fatlawi, A. N. (2010b). Geological and hydrogeological characteristics of Umm Er Radhuma aquifer West of Iraq. *Euphrates Journal of Agriculture Science, 2*(4), 12–20.

Ali, M. E., & Abdel-Hameed, M. (2018). The potential of nitrate removal from groundwater of Bani-Suif west area, Egypt using nanocomposite reverse osmosis membranes. *Journal of Basic and Environmental Sciences, 5,* 230–239.

Al-Ibrahim, A. A. (1991). Excessive use of groundwater resources in Saudi Arabia: Impacts and policy options. *Ambio*, *20,* 34–37.

Al-Sayari, S. S., & Zötl, J. (1978). *Quaternary period in Saudi Arabia. Sedimento-logical, hydrogeological, hydrochemical, geomorphological, and climatological investigations in Central and Eastern Saudi Arabia* (Vol. 1). New York: Springer.

Alsharhan, A. S., Rizk, Z. A., Nairn, A. E. M., Bakhit, D. W., & Alhajari, S. A. (2001). *Hydrogeochemistry. Hydrogeology of an Arid Region: The Arabian Gulf and adjoining areas*. Amsterdam: Elsevier. https://doi.org/10.1016/b978-044450225-4/50006-3.

Amin, M. T., Alazba, A. A., & ElNesr, M. N. (2013). Adaptation of climate variability/extreme in arid environment of the Arabian peninsula by rainwater harvesting and management. *International Journal of Environmental Science and Technology, 10*(1), 27–36.

Apaydın, A. (2012). Dual impact on the groundwater aquifer in the Kazan Plain (Ankara, Turkey): Sand–gravel mining and over-abstraction. *Environmental Earth Sciences, 65*(1), 241–255.

Awad, S. R. (2019). Groundwater hydrogeology and quality in Helwan area and its vicinities in Egypt. *Water Science, 33*(1), 10–21.

Awadh, S. M. (2018). A preliminary assessment of the geochemical factors affecting groundwater and surface water quality around the rural communities in Al-Anbar, Western Desert of Iraq. *Environmental Earth Sciences, 77*(3), 83.

Awadh, S. M., Abdulhussein, F. M., & Al-Kilabi, J. A. (2016). Hydrogeochemical processes and water-rock interaction of groundwater in Al-Dammam aquifer at Bahr Al-Najaf, Central Iraq. *Iraqi Bulletin of Geology and Mining, 12*(1), 1–15.

Bakiewicz, W., Milne, D. M., & Noori, M. (1982). Hydrogeology of the Umm Er Radhuma aquifer, Saudi Arabia, with reference to fossil gradients. *Quarterly Journal of Engineering Geology and Hydrogeology, 15*(2), 105–126.

Baniasad, A., Rabbani, A., Sachse, V. F., Littke, R., Moallemi, S. A., & Soleimany, B. (2016). 2D basin modeling study of the Binak Trough, northwestern Persian Gulf, Iran. *Marine and Petroleum Geology, 77,* 882–897.

Bates, B., Kundzewicz, Z., & Wu, S. (2008). *Climate change and water*. Intergovernmental panel on climate change secretariat. Technical paper, IPCC Secretariat, Geneva, 210 p.

Beaumont, P. (1977). Water and development in Saudi Arabia. *Geographical Journal, 143,* 42–60.

Bedaso, Z. K., Wu, S.-Y., Johnson, A. N., & McTighe, C. (2019). Assessing groundwater sustainability under changing climate using isotopic tracers and climate modelling, southwest Ohio, USA. *Hydrological Sciences Journal, 64*(7), 798–807.

Berndes, G. (2008). Water demand for global bioenergy production: Trends, risks and opportunities. *Energy for Sustainable Development, 4,* 64–71.

Buday, T. (1980). *The regional geology of Iraq: Stratigraphy and paleogeography* (Vol. 1). Bagdad: State Organization.

Chowdhury, S., & Al-Zahrani, M. (2015). Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia. *Journal of King Saud University-Engineering Sciences, 27*(1), 68–82.

Das, B., & Pal, S. C. (2019). *Assessment of groundwater recharge and its potential zone identification in groundwater-stressed Goghat-I block of Hugli District, West Bengal* (pp. 1–19). Development and Sustainability: India. Environment.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society, 137*(656), 553–597.

DeNicola, E., Aburizaiza, O. S., Siddique, A., Khwaja, H., & Carpenter, D. O. (2015). Climate change and water scarcity: The case of Saudi Arabia. *Annals of Global Health, 81*(3), 342–353.

DeNicola, E., & Subramaniam, P. R. (2014). Environmental attitudes and political partisanship. *Public Health, 128*(5), 404–409.

Dirks, H. (2007). *Hydrochemistry of the Tertiary Aquifer System in the Eastern Part of the Arabian Peninsula*. Diploma Thesis, Darmstadt, 72 p.

Dirks, H., Al Ajmi, H., Kienast, P., & Rausch, R. (2018). Hydrogeology of the Umm Er Radhuma aquifer (Arabian peninsula). *Grundwasser, 23*(1), 5–15.

El-Ashry, M., & Saab, N. Z. (2010). *Arab environment: Water: Sustainable management of a scarce resource*. Beirut: Arab Forum for Environment and Development (AFED).

ESCWA, & BGR. (2013). Inventory of Shared Water Resources in Western Asia: 1-Euphrates River Basin. *Inventory of Shared Water Resources in Western Asia*, pp. 47–78. http://waterinventory.org/

Ghorbani, M. A., Deo, R. C., Yaseen, Z. M., & Kashani, M. H. (2017). Pan evaporation prediction using a hybrid multilayer perceptron-firefly algorithm (MLP-FFA) model: Case study in North Iran. https://doi.org/10.1007/s00704-017-2244-0

Giorgi, F. (2006). Climate change hot-spots. *Geophysical research letters*, *33*(8), 1–4.

Helmreich, B., & Horn, H. (2009). Opportunities in rainwater harvesting. *Desalination*. https://doi.org/10.1016/j.desal.2008.05.046.

Idrotechneco, C. P. (1977). *Hydrogeological exploration (Block 4).* Final report. GEOSURV, international reports (26).

IEA, OPEC, OECD, and World Bank. (2010). Analysis of the scope of energy subsidies and suggestions for the G-20 initiative, Joint Reportprepared for submission to the G-20 Summit Meeting Toronto (Canada), 26-27 June 2010 (pp. 1–81).

IPCC. (2007). Climate change 2007: The physical science basis. *Intergovernmental Panel on Climate Change, 446*(7137), 727–728. https://doi.org/10.1038/446727a.

Kalbus, E., Oswald, S., Wang, W., Kolditz, O., Engelhardt, I., Al-Saud, M. I., et al. (2011). Large-scale modeling of the groundwater resources on the Arabian platform. *International Journal of Water Resources and Arid Environments, 1*(1), 38–47.

Kalhor, K., & Emaminejad, N. (2019). Sustainable development in cities: Studying the relationship between groundwater level and urbanization using remote sensing data. *Groundwater for Sustainable Development*, *9*, 100243.

Kent, P. (1970). The salt plugs of the Persian Gulf region. *Leicester Literary and Philosophical Society Transactions*, *64*, 56–88.

Khan, Q., Kalbus, E., Alshamsi, D. M., Mohamed, M. M., & Liaqat, M. U. (2019). Hydrochemical analysis of groundwater in Remah and Al Khatim Regions, United Arab Emirates. *Hydrology, 6*(3), 60.

Koohafkan, A. P. (1996). *Desertification, drought and their consequences*. Rome: Sustainable Development, Food and Agriculture Organization (FAO).

Krasny, J., Alsam, S., & Jassim, S. Z. (2006). *Hydrogeology. Geology of Iraq* (1st ed.). Prague: Published by Dolin, Prague and Moravian Museum.

Krishnamurthy, J., & Srinivas, G. (1995). Role of geological and geomorphological factors in ground water exploration: a study using IRS LISS data. *International Journal of Remote Sensing, 16*(14), 2595–2618.

Kummerow, C., Barnes, W., Kozu, T., Shiue, J., & Simpson, J. (1998). The tropical rainfall measuring mission (TRMM) sensor package. *Journal of Atmospheric and Oceanic Technology, 15*(3), 809–817.

Lanjwani, M. F., Khuhawar, M. Y., Jahangir Khuhawar, T. M., Lanjwani, A. H., Jagirani, M. S., Kori, A. H., et al. (2019). Risk assessment of heavy metals and salts for human and irrigation consumption of groundwater in Qambar city: A case study. *Geology, Ecology, and Landscapes*. https://doi.org/10.1080/24749508.2019.1571670.

Margat, J., & Van der Gun, J. (2013). *Groundwater around the world: A geographic synopsis*. Boca Raton: CRC Press.

Middleton, N. J., & Thomas, D. S. (1992). *World atlas of desertification* (United nations environment program). Wiley Online Library, Edward, Arnold, London.

Naganna, S. R., Deka, P. C., Ch, S., & Hansen, W. F. (2017). Factors influencing streambed hydraulic conductivity and their implications on stream–aquifer interaction: a conceptual review. *Environmental Science and Pollution Research, 24*(32), 24765–24789.

Nairn, A. E. M., & Alsharhan, A. S. (1997). *Sedimentary basins and petroleum geology of the Middle East*. Amsterdam: Elsevier.

Niaz, A., Khan, M. R., Ijaz, U., Yasin, M., & Hameed, F. (2018). Determination of groundwater potential by using geoelectrical method and petrographic analysis in Rawalakot and adjacent areas of Azad Kashmir, sub-Himalayas, Pakistan. *Arabian Journal of Geosciences, 11*(16), 468.

Odhiambo, G. O. (2016). Water scarcity in the Arabian Peninsula and socio-economic implications. *Applied Water Science*. https://doi.org/10.1007/s13201-016-0440-1.

Pande, C. B., Moharir, K. N., Singh, S. K., & Varade, A. M. (2019). *An integrated approach to delineate the groundwater potential zones in Devdari watershed area of Akola district, Maharashtra* (pp. 1–21). Development and Sustainability: Central India. Environment.

Pike, J. G. (1985). Groundwater resources and development in the central region of the Arabian Gulf. *Congress of the International Association of Hydrogeologists* (Vol. 18, pp. 46–55). Houston: IAH.

Qutbudin, I., Shiru, M. S., Sharafati, A., Ahmed, K., Al-Ansari, N., Yaseen, Z. M., et al. (2019). Seasonal drought pattern changes due to climate variability: Case study in Afghanistan. *Water, 11*(5), 1096. https://doi.org/10.3390/w11051096.

Raghavendra, N. S., & Deka, P. C. (2015). Sustainable development and management of groundwater resources in mining affected areas: A review. *Procedia Earth and Planetary Science*. https://doi.org/10.1016/j.proeps.2015.06.061.

Raghavendra, N. S., & Deka, P. C. (2016). Multistep ahead groundwater level time-series forecasting using gaussian process regression and ANFIS. *Advances in Intelligent Systems and Computing*. https://doi.org/10.1007/978-81-322-2653-6_19.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management, 80*(1–3), 5–22.

Salih, S. Q., Allawi, M. F., Yousif, A. A., Armanuos, A. M., Saggi, M. K., Ali, M., et al. (2019). Viability of the advanced adaptive neuro-fuzzy inference system model on reservoir evaporation process simulation: Case study of Nasser Lake in Egypt. *Engineering Applications of Computational Fluid Mechanics, 13*(1), 878–891. https://doi.org/10.1080/19942060.2019.1647879.

Sayl, K. N., Muhammad, N. S., Yaseen, Z. M., & El-shafie, A. (2016). Estimation the physical variables of rainwater harvesting system using integrated GIS-based remote sensing approach. *Water Resources Management, 30*(9), 3299–3313. https://doi.org/10.1007/s11269-016-1350-6.

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., et al. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes: An International Journal, 20*(15), 3335–3370.

Schulz, S. (2017). *Experimental and numerical studies on the water balance of the Upper Mega Aquifer system*. Arabian Peninsula: Technische Universität.

Schulz, S., Horovitz, M., Rausch, R., Michelsen, N., Mallast, U., Köhne, M., et al. (2015). Groundwater evaporation from salt pans: Examples from the eastern Arabian Peninsula. *Journal of Hydrology, 531,* 792–801.

Sharland, P. R., Archer, R., Casey, D. M., Davies, R. B., Hall, S. H., Heward, A. P., et al. (2001). Sequence stratigraphy of the Arabian Plate. *GeoArabia, 2,* 371.

Shubber, S. (2009). *The law of investment in Iraq*. Leiden: Brill.

Sissakian, V. K., & Mohammed, B. S. (2007). Stratigraphy. *Iraqi Bulletin of Geology and Mining, 3,* 51–124.

Sowers, J., Vengosh, A., & Weinthal, E. (2011). Climate change, water resources, and the politics of adaptation in the Middle East and North Africa. *Climate Change, 104*(3–4), 599–627. https://doi.org/10.1007/s10584-010-9835-4.

Sulaiman, S. O., Shiri, J., Shiralizadeh, H., Kisi, O., & Yaseen, Z. M. (2018). Precipitation pattern modeling using cross-station perception: Regional investigation. *Environmental Earth Sciences*. https://doi.org/10.1007/s12665-018-7898-0.

Taniguchi, M., Burnett, W. C., Cable, J. E., & Turner, J. V. (2002). Investigation of submarine groundwater discharge. *Hydrological Processes, 16*(11), 2115–2129.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., et al. (2013). Ground water and climate change. *Nature Climate Change, 3*(4), 322.

Tolba, M. K. (1992). *Saving our planet: Challenges and hopes*. New York: Springer.

Ukayli, M. A., & Husain, T. (1988). Comparative evaluation of surface water availability, wastewater reuse and desalination in Saudi Arabia. *Water International, 13*(4), 218–225.

UN-ESCWA, B. G. R. (2013). *Inventory of shared water resources in Western Asia: Chapter 6 Jordan River Basin*. Beirut: United Nations Economic and Social Commission for Western Asia. Federal Institute for Geosciences and Natural Resources.

Wada, Y., & Heinrich, L. (2013). Assessment of transboundary aquifers of the world—Vulnerability arising from human water use. *Environmental Research Letters, 8*(2), 24003.

Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1999). *Comprehensive test of phonological processing: CTOPP*. Austin: PRO-ED.

WRI, I. (1999). *UNEP (1992) Global biodiversity strategy. Guidelines for action to save, study and use earth's biotic wealth sustainably and equitably*. Washington, DC: World Resources Institute.

Zaharani, K. H., Al-Shayaa, M. S., & Baig, M. B. (2011). Water conservation in the Kingdom of Saudi Arabia for better environment: Implications for extension and education. *Bulgarian Journal of Agricultural Science, 17*(3), 389–395.