Water resources and the potential of brackish groundwater extraction in Egypt: a review
A. Nashed, A. B. Sproul and G. Leslie

ABSTRACT
A review of water resources in Egypt indicates that Nile water is fully utilized and the available quantity could potentially decrease by approximately 19% due to proposed water usage by neighboring countries. Seawater desalination and groundwater extraction are the only options to increase Egypt’s water supply. The extraction and desalination of brackish groundwater is suggested to develop sustainable decentralized communities. A review of seven main hydro-geological systems across six regions in Egypt is conducted to identify areas with access to brackish groundwater and aquifers are ranked on the potential for sustainable development using multi-criteria analysis based on literature data for productivity, renewability, groundwater depth and development potential. Approximately 55% of Egypt’s area has access to brackish groundwater, 47% of which has access to aquifers with moderate to high potential for development. Five high priority areas have been identified for establishing decentralized communities based on brackish groundwater extraction: Areas with access to the Nubian aquifer, the Quaternary aquifer in the central parts of the Sinai Peninsula, in the vicinity of the Nile River in the Eastern Desert and the Western Desert south of Cairo, and the coastal aquifers along the north west Mediterranean coast and the Suez Gulf.

Key words | brackish groundwater, decentralization, desalination, Egypt, solar energy, sustainable development

INTRODUCTION
Egypt in the 20th century held sufficient water resources and energy reserves to support urban and agricultural development. However, in the 21st century an expanding population has increased the demand for fresh water, eroded reserves of surplus oil and, is consuming natural gas supplies at a rate that will exhaust the estimated reserves by 2032 – based on data reported in the literature (British Petroleum 2012; US Energy Information Administration 2012). Population pressures on fuel and electricity infrastructure have caused intermittent shortages in transport fuels and butane cooking gas as well as power outages in summer peak hours (El-Behary 2012; Leila 2012; Sabry 2012). Moreover, the reliance on low quality water for irrigation, caused by the shortage of water, and urban encroachment into agricultural areas have reduced the availability of arable lands resulting in a net increase in annual food imports (Lenney et al. 1996; Amin 2010; Viney 2012). Increasing shortages in fuel, water and food coupled with a devaluation in the national currency and an expected reduction in government subsidies as a result of declining export income and government revenue (Bradley 2012; Coleman 2012) will have the greatest impact on rural areas that are home to 57% of the population and approximately 70% of those who live at or below the poverty line (Rural Poverty Portal 2010).

Economic revival through the development of sustainable and autonomous decentralized agricultural communities removed from the heavily populated Nile valley and delta could alleviate rural poverty levels. Schumacher (1974) argued that the development of decentralized communities increases the resiliency of the population particularly when the workplace is in the area where people are living.
and where local skills could be exploited. For this reason the development of decentralized agricultural communities is suggested as one third of Egypt’s workforce are in the agriculture sector (FAO AQUASTAT 2005) and are mostly concentrated in rural areas (Shalaby et al. 2011). Creating decentralized communities away from the Nile valley and delta area will also prevent further degradation of arable lands and will result in a redistribution of the population, 97% of which are currently concentrated in less than 4% of the country (Abdel-Wahaab & Omar 2010). The development of such communities is contingent upon access to reliable supplies of potable water.

This paper critically examines the availability of water resources in Egypt and assesses the potential for brackish groundwater (GW) to be the main water resource for the proposed decentralized communities. The seven main hydro-geological systems across six regions in Egypt are reviewed. Brackish GW aquifers are identified and ranked based on their potential for sustainable water extraction. A similar study was carried out by Salim (2011) to assess the site appropriateness for solar driven brackish GW extraction in Egypt considering factors such as GW depth, GW salinity, distance from the Nile valley and delta and solar resources. This paper extends on the study by Salim (2011) with a greater focus on the potential of sustainable extraction of brackish GW in terms of productivity and renewability. The paper concludes with a comparison between brackish GW extraction and desalination, and seawater desalination.

**Water status in Egypt**

Egypt is an arid country (Hefny et al. 1992) with limited water resources. In 2002, the per capita water share dropped to 829 m$^3$/year which is below the level associated with countries with chronic water shortages (Mason 2004). The main supply of fresh water in Egypt is the Nile River. Water supplies are augmented by GW extraction and seawater desalination. In addition, water from the Nile is reused to improve overall Nile water utilization.

**Nile water**

In 2000, extraction of Nile water accounted for 74% of Egypt’s overall water demand, and with subsequent reuse its utility extended to meet 98% of the demand (Allam & Allam 2007). However, the steady increase in water demand driven by population growth has resulted in full allocation of Egypt’s quota of the Nile water that is capped at 55.5 billion m$^3$/year by the 1959 agreement with Sudan, which was a single country at that time (El-Kady & El-Shibini 2001; Hamza & Mason 2004; Dawoud et al. 2005).

Egypt’s quota could be reduced if any of the other Nile basin countries, which were not part of the 1959 agreement, construct dams to impound flow. These countries include Congo, Kenya, Rwanda, Burundi, Tanzania, Uganda, Eritrea, Ethiopia and South Sudan (now that South Sudan is a separate country, it is likely that the 1959 agreement only includes the Republic of Sudan). Recently, Ethiopian officials announced the initiation of the ‘Grand Renaissance Dam’ (GRD) project on the Blue Nile, where approximately 85% of the Nile water originates (Abu Zeid 1992; Whittington & McClelland 1992), which aims to generate 6,000 MW of hydropower (Ethiopian Electric Power Corporation 2013). Construction of the dam will have a short term and a long term effect on surface water supplies in Egypt and the Republic of Sudan. The first effect is a temporary reduction in flow as the Blue Nile water is diverted to fill the reservoir. The reservoir capacity is reported to be 74 billion m$^3$ (Ethiopian Electric Power Corporation 2013) and Ethiopian officials are aiming to fill the reservoir within 5–6 years (Davison 2013) resulting in 10.5 to 12.6 billion m$^3$/year less flow to Egypt and the Republic of Sudan (taking into account that the Blue Nile contributes by only 85% to the overall Nile water reaching the Aswan dam) which would be equivalent to an approximately 12.5 to 15% decrease in Egypt’s annual Nile water share, assuming the same distribution of the Nile water as in the 1959 agreement i.e. 66.1% Egypt’s share, 22% Republic of Sudan’s share and the rest to account for evaporation losses. The second effect is a permanent reduction in Nile water share due to evaporation losses from the reservoir. At present there are no detailed estimations of the evaporation losses, but figures of 1.7 (Virgu 2012), 2.5 (Gleick 2013) and 3 (Yousif 2012) billion m$^3$/year have been reported without any indication of the methodology used in the estimation process. Using the simplified correlation derived by Linacre (1977) (which showed that the maximum deviation from values estimated by his correlation was 0.3 mm/day which
is less than 0.2 billion m\(^3\)/year for the Grand Renaissance reservoir’s area and allowing us to conclude that the correlation has good accuracy) combined with climate data from the National Renewable Energy Laboratory website (NREL 2013), we estimated the annual evaporation losses from the reservoir’s 1,680 km\(^2\) (Ethiopian Electric Power Corporation 2013) surface area to be approximately 4.1 billion m\(^3\)/year. This means that Egypt’s Nile water share would permanently decrease by approximately 2.5 billion m\(^3\)/year. The Nile annual flow to Egypt would decrease furthermore if water from the reservoir would be used by Ethiopia for land reclamation, which is expected to happen for the following reasons: first, according to Mason (2004) Ethiopia has large development plans to meet its increasing demand of food especially that its irrigation is currently relying on rainfall which is irregular and unreliable; and, second, the initial proposal by the United States Bureau of Reclamation for building dams in Ethiopia to control the Blue Nile water included the use of the stored water for irrigating 434,000 hectares of land (Whittington & McClelland 1992). The United States Bureau of Reclamation concluded that the development of such irrigation projects would decrease the annual flow to Egypt and Sudan (which was one country at the time of the study) by 4 billion m\(^3\)/year including evaporation losses from the reservoirs formed by the dams, which would lead to an approximately 4.8% decrease in Egypt’s Nile water share assuming the given distributions of the 1959 agreement. However, these values could be underestimated given that, based on the approximated method to determine the amount of water needed for irrigation discussed in Brouwer et al. (1992), irrigating 434,000 hectares of land with Ethiopia’s climate conditions would typically require 13.4 billion m\(^3\)/year assuming that the water efficient sprinkler irrigation method and lined canals to transport the water would be used which have 75 and 95% efficiency, respectively (Brouwer et al. 1989). An irrigation water use of 0.75 l/s/ha was used, which is an average value between that required during a monsoon climate dry season and a monsoon climate wet season (Brouwer et al. 1989). In this case, Egypt’s Nile water share could decrease by 18.7% assuming the conditions listed previously including the evaporation losses. Droughts in watershed areas may also decrease Egypt’s Nile water share which happened during 1976 to 1987 and led to about 6.9 billion m\(^3\)/year decrease in the amount of Nile water discharged from the Aswan Dam (Abu Zeid 1992).

There are a few projects, however, that could increase Egypt’s annual share of Nile water, mainly the Jonglei canal, Bahr-El-Ghazal and Machar swamps projects. These projects aim to increase the amount of water reaching the Nile River mainly through reducing evaporation losses in southern Sudan. The expected increase in the Nile flow by these projects is estimated, according to Abu Zeid (1992), to be 18 billion m\(^3\)/year to be shared between the pre-division Sudan and Egypt. However, according to Allam & Allam (2007), these projects are unlikely to be carried out in the near future due to political, ecological and socio-economic issues, which are discussed in detail in the literature (Whittington & McClelland 1992, Swain 1997).

Nile water reuse

Due to the full exploitation of Nile water, Egypt has relied on Nile water reuse, as it is considered to be the most economical and efficient way to increase water availability (Mason 2004). Nile water reuse consists of reusing excess irrigation water along the Nile flood plain which flows back to the Nile River as well as irrigation canals and drains where the water is reused directly in irrigation or after mixing with Nile water to improve its quality. There is an estimated 21.5 billion m\(^3\)/year of water that flows back to the Nile River, irrigation canals and drains, out of which 16.5 billion m\(^3\)/year is found in the drains in the delta area (Abdel-Azim & Allam 2004). The remaining 5 billion m\(^3\)/year directly flows back to the Nile River in the Nile valley area (Allam & Allam 2007). The reusable amount of water from the drains in the delta area is, however, limited to 8.5 billion m\(^3\)/year as a minimum amount of about 8 billion m\(^3\)/year should be discharged into the Mediterranean Sea to avoid seawater back flow into the Nile River’s branches and canals and to keep low salinity levels in the northern lakes which are used as fisheries (Abdel-Azim & Allam 2004). The available reusable amount of Nile water is therefore 13.5 billion m\(^3\)/year out of which 12.5 billion m\(^3\)/year has been reported by Allam & Allam (2007) to be used in 2000 and based on personal communication with the Ministry of Water Resources and Irrigation (MWRI
2010; personal communication, 23 August 2012), an approximate amount of 13 billion m³/year was used in 2010.

The available quantity of reused Nile water that is suitable for drinking and irrigation is also decreasing due to pollution caused by domestic and industrial effluents discharged into the Nile River, described as the main recipient of sewage water in Egypt, and drains in the delta (Wahaab & Badawy 2004; United Nations Country Team 2005; Abdel-Shafy & Aly 2007), knowing that in 2011/2012 about only half of the discharged waste water was treated (Khalifa 2011a; Egypt State Information Service n.d.; Abdel-Wahaab 2012). For this reason, domestic and industrial waste water is not included in the water budget shown in Table 1 and is assumed to be a part of the available water in the Nile River and drains in the delta except treated waste water that has been reported to be directly used in irrigation in the reclaimed lands in desert areas as it is unlikely to be recycled back to the Nile River. The assumption is because part of the wastewater has been reported to be also discharged in northern lakes or in open pits, hence cannot be recycled; however, the amount is likely to be small.

**Groundwater extraction**

Excess irrigation water is also reused indirectly through GW extraction from the Nile basin aquifer which is mainly recharged by excess irrigation water and seeping water from irrigation canals and drains (Hefny et al. 1992). The Nile basin aquifer, which has an estimated capacity of 400 billion m³ (Masoud et al. 2003), acts as a storage reservoir to accumulate the otherwise wasted Nile water (Elewa & El Nahry 2009). In 2009, 7 billion m³/year was extracted from the Nile basin aquifer (Ministry of Water Resources and Irrigation 2010) while the maximum renewable amount of GW in the aquifer is estimated to be 7.5 billion m³/year (Mostafa et al. 2004). The available amount that is suitable for drinking and irrigation is also decreasing due to pollution caused by the excessive use of fertilizers in irrigation, leakage from old sewage networks in urban areas and direct sewage dumping to the ground in rural areas, that in addition to salinization of GW in the delta area caused by seawater intrusion (Sherif & Singh 2002; Wahaab & Badawy 2004; Abdalla et al. 2009).

Extracting fossil and rainfall renewed GW is another important source of water especially in border cities (United Nations Country Team 2005). The overall extracted fossil and rainfall renewed GW has been estimated to be at least 1.8 billion m³/year while the estimated exploitable GW reserves could exceed 5.46 billion m³/year (Nour & Khattab 1998; Hefny & Shata 2004; FAO AQUASTAT 2005). Therefore, while fossil and rainfall renewed GW represents a small percentage of the currently available water in Egypt, it is a highly underutilized water resource and hence can play a larger role in meeting Egypt’s water demand. For example, the estimated exploitable amount of GW could meet the domestic and agricultural water demands of approximately 19% of the current population based on average water consumption values reported in Fraenkel & Thake (2006). Furthermore, larger amounts of GW reserves could be available as not all aquifers in Egypt are assessed for their GW reserves, especially areas containing brackish GW, the main focus of this study.

**Seawater desalination**

Seawater desalination is the remaining option for Egypt to indefinitely increase its water resources. Seawater desalination currently accounts for 0.35% of Egypt’s available water resources based on latest data from the International Desalination Association inventory (2013). While seawater resources are abundant, expansion of desalination capacity in Egypt is constrained by costs, and therefore seawater desalination is limited to installations that are insensitive to high prices. These include tourist areas on the Red Sea and Suez Gulf where 58.5% of seawater desalination plants are located, municipalities mainly located in remote coastal areas (24%) and industrial use (12%).

**Brackish groundwater in Egypt**

Groundwater in Egypt is found in seven main hydrogeological systems: the Nubian sandstone aquifer, the fissured carbonate aquifer, the basement fissured hard rock aquifer, the Al-Moghra aquifer and the Quaternary aquifer, which includes the Nile basin aquifer, the alluvial deposits aquifers and most of the coastal aquifers. Figure 1 shows the main aquifers in Egypt and is based on the
Table 1 | Summary of water resources availability and usage in Egypt

<table>
<thead>
<tr>
<th>Water source</th>
<th>Current water availability (billion m³/year)</th>
<th>Water used (billion m³/year)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile water</td>
<td>55.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>55.5</td>
<td>• Nile water share could increase to 65.1&lt;sup&gt;b&lt;/sup&gt; billion m³/year through projects aiming to decrease evaporation losses in Nile basin countries and assuming that the GRD will be used only for hydro-electricity generation. Conversely, if Ethiopia used the stored water from the dam in irrigation and the aforementioned projects are not carried out, Nile water share may decrease to an amount ranging from 45.1 to 52.9 billion m³/year.</td>
</tr>
<tr>
<td>Nile water evaporation losses</td>
<td>–2&lt;sup&gt;c&lt;/sup&gt; to –3&lt;sup&gt;d&lt;/sup&gt;</td>
<td>–2 to –3</td>
<td>• 0.3 billion m³/year is the minimum flow needed for navigation after implementing proper measures to control Nile flow&lt;sup&gt;e&lt;/sup&gt;. It is not clear, however, whether such measures are already implemented or not.</td>
</tr>
<tr>
<td>Nile flow needed for navigation</td>
<td>–0.3&lt;sup&gt;c&lt;/sup&gt;</td>
<td>–0.3, –4&lt;sup&gt;e&lt;/sup&gt;</td>
<td>• Average precipitation in Egypt amounts to 51 billion m³/year&lt;sup&gt;f&lt;/sup&gt;. The available amount of usable rainfall could therefore increase if measures are taken to improve rainfall utilization such as the use of dams, storage tanks, ponds and cisterns&lt;sup&gt;g&lt;/sup&gt;.</td>
</tr>
<tr>
<td>Rainfall (including groundwater recharge)</td>
<td>1.8&lt;sup&gt;e,f&lt;/sup&gt;</td>
<td>&gt;0.165&lt;sup&gt;g&lt;/sup&gt;</td>
<td>• 0.3 billion m³/year is the minimum flow needed for navigation after implementing proper measures to control Nile flow&lt;sup&gt;e&lt;/sup&gt;. It is not clear, however, whether such measures are already implemented or not.</td>
</tr>
<tr>
<td>Reuse of Nile water through groundwater extraction</td>
<td>7.5&lt;sup&gt;i,j&lt;/sup&gt;</td>
<td>7 (2009)&lt;sup&gt;k&lt;/sup&gt;</td>
<td>• The maximum amount could potentially decrease as Nile water is being diverted to Toshka and Al-Salam canals.</td>
</tr>
<tr>
<td>Reuse of Nile water directly flowing back to the river, canals and drains</td>
<td>13.5&lt;sup&gt;j&lt;/sup&gt;</td>
<td>13&lt;sup&gt;m&lt;/sup&gt; (2010)</td>
<td>• Water treatment and/or pollution control is required to fully use the available amount.</td>
</tr>
<tr>
<td>Directly used treated waste water</td>
<td>0.7&lt;sup&gt;n&lt;/sup&gt; (2000)–1.3&lt;sup)o&lt;/sup&gt;</td>
<td>0.7 (2000)–1.3</td>
<td>• Increasing treated waste water will not necessarily increase the water supply as most waste water flows back to the Nile River and drains and is counted as part of the reused Nile water.</td>
</tr>
<tr>
<td>Desalinated seawater</td>
<td>0.275 (2013)&lt;sup&gt;p&lt;/sup&gt;</td>
<td>0.275 (2013)&lt;sup&gt;p&lt;/sup&gt;</td>
<td>• Essentially indefinite potential.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Economic limits.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Seawater desalination capacity to increase to 0.32 billion m³/year by 2016&lt;sup&gt;p&lt;/sup&gt;.</td>
</tr>
</tbody>
</table>

(continued)
Table 1 | continued

<table>
<thead>
<tr>
<th>Water source</th>
<th>Current water availability (billion m³/year)</th>
<th>Water used (billion m³/year)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil groundwater</td>
<td>2.7³ to &gt;4.16³</td>
<td>&gt;1.6³</td>
<td>• Further studies required to estimate the available GW reserves especially in the Sinai Peninsula and the Eastern Desert.</td>
</tr>
<tr>
<td>Total</td>
<td>78.7 to &gt;81.7</td>
<td>71.2 to &gt;76.5</td>
<td></td>
</tr>
</tbody>
</table>

³Swain (1997).
²Assuming the same Nile water distribution as in 1959 agreement given above. Value includes evaporation losses from the GRD reservoir.
⁵FAO AQUASTAT (2005).
⁶Value includes 1.3 billion m³/year recharging the aquifers and 0.5 billion m³/year recharging surface waters.
⁷Hefny & Shata (2004); Abdallah (2006). It has been assumed that approximately all GW extracted from the Sinai Peninsula and the Eastern Desert is rainfall renewed GW.
⁸Sonbol (2009).
⁹Mostafa et al. (2004).
¹⁰Possible overlap with available Nile water (55.5 billion m³/year) as the Nile basin aquifer is also directly recharged by Nile water seepage in some locations.
¹¹Ministry of Water Resources and Irrigation (2010).
¹³MWRI (2010), personal communication, 23 August.
¹⁴Khalifa (2011a).
¹⁵Egypt State Information Service (n.d.).
¹⁶International Desalination Association (2013).
¹⁷Nour & Khattab (1998); Hefny & Shata (2004).
¹⁸Value only includes fossil GW extracted from the Western Desert.
Figure 1 | Hydro-geological map of Egypt. Base map of Egypt modified after © 2007 World Trade Press All Rights Reserved.
hydro-geological map from the Research Institute for Groundwater (RIGW) (1988) in addition to the studies by Gheith & Sultan (2002) and Sultan et al. (2008) which were used to identify the alluvial deposits Quaternary aquifer in the main wadis, or drainage basins, in the Eastern Desert.

Brackish water is defined by the US Geological Survey as those with salinities ranging from 1,000 to 10,000 mg l\(^{-1}\) (Carter et al. 2005). Aquifer productivity and surface recharge were mainly based on the qualitative data compiled by RIGW (1988). The data were complemented by more recent quantitative and qualitative data available in the literature. To relate quantitative and qualitative data, qualitative descriptions were compared to available well productivities and rainfall recharge estimates reported in the literature for the same region to get a rough estimate on the equivalent range related to each description. For example, well yields less than 5 m\(^3\)/h are reported in areas described to have low productivity while areas described to highly productive have well yields with average values exceeding 150 m\(^3\)/h, accordingly quantitative values could be roughly assigned to each description.

**Nubian sandstone aquifer**

The Nubian sandstone aquifer is the most important source of GW in areas away from the Nile valley and delta (Hefny & Shata 2004) and stretches over the Western Desert, Eastern Desert and the Sinai Peninsula and also to neighboring Libya, Chad, Saudi Arabia and the Republic of Sudan. GW reserves in the Nubian aquifer in Egypt are estimated to be at least 200,000 billion m\(^3\) and are mainly non-renewable. However, as GW in the Nubian aquifer is shared with other countries, there could be a limit imposed on the amount of GW that could be annually extracted by each country (Shata 1982; Hefny et al. 1992; Hassan et al. 2004).

In the Western Desert, the Nubian aquifer stretches over the entire desert and is mainly unconfined south of 25° latitude where the aquifer outcrops, then it becomes confined northward where it is overlain by the fissured carbonate aquifer (Figure 1) (Nour 1996; Sultan et al. 2007). According to Shata (1982) and Nour & Khattab (1998), the Nubian aquifer contains brackish GW (1,000 to 10,000 mg l\(^{-1}\)) within a narrow belt stretching along the Al-Qattara depression north of latitude 29° then southward along the Nile River western bank. In the north of the Al-Qattara Depression and El-Minya city, GW becomes saline and hyper saline. South of latitude 29°, the Nubian GW is fresh (<1,000 mg l\(^{-1}\)) and is mainly exploited from the New Valley oases (Hefny et al. 1992). Shata (1982) and Nour & Khattab (1998) also show that the Nubian aquifer is a deep aquifer system where well depths in the oases area range from 250 to 1,000 m below ground level (BGL) while at the Al-Qattara depression area, the GW is found at even larger depths that could exceed 2 km. However, as the aquifer is mainly confined, GW in most wells is flowing above ground level while in the unconfined area the depth to water table in the brackish water zone ranges from 30 to 110 m BGL (actual depth data are with respect to mean sea level therefore the depths with respect to ground level were approximately estimated based on ground elevation). The Nubian aquifer in the Western Desert is a highly productive aquifer with reported average well yields exceeding 150 m\(^3\)/h in the oases area (Nour & Khattab 1998) and therefore, assuming similar aquifer properties as the fresh GW zone, the brackish GW zone is likely to be as highly productive. Moreover, the aquifer has a high development potential where for example in the New Valley oases, one of the most important sites from which GW is extracted, approximately half of the estimated amount that could be economically exploited was reported to be extracted (Hefny & Shata 2004) while the brackish GW zone is likely to be unexploited as no wells in this zone were reported in the literature.

In the Eastern Desert, the Nubian aquifer outcrops in the southern parts but further north near Qena city the aquifer is overlain by the fissured carbonate aquifer (Figure 1). While the aquifer is mainly non-renewable, it receives some recharge by occasional infiltrating rainfall particularly where the aquifer outcrops (Abdel-Moneim 2005). The Nubian aquifer in the Eastern Desert mainly contains brackish water (1,000 to 10,000 mg l\(^{-1}\)) (Hefny et al. 1992) except north of El-Minya city where the GW is mainly saline based on the aquifer’s fresh /saline GW boundary line shown in Sultan et al. (2007). The depth to water table has been only reported in the main wadis north of Aswan city where the aquifer is confined and it ranges from 20 to 50 m BGL while the depth to top aquifer is only reported in Qena.
area and ranges from 100 to 250 m BGL (Hefny & Shata 2004). However, based on schematic cross-sectional maps and well depth data from Sultan et al. (2000, 2007), the depth to the top of the Nubian aquifer is likely to exceed 1 km BGL north of Qena city except near the areas where the aquifer outcrops. Regarding the aquifer’s productivity, while the Nubian aquifer in the Eastern Desert is described by RIGW (1988) to be moderately to highly productive similar to its counterpart in the Western Desert, test wells in wadi Qena and wadi Hammamat have well yields ranging from 2.7 to 83 m³/h (Idris & Nour 2003). Nonetheless, the Nubian aquifer in the Eastern Desert in general is likely to have lower GW reserves than in the Western Desert. For example, in the East Oweinat area located south of the Western Desert and occupying an area of about 16,000 km² (Nour & Khattab 1998), it is estimated that an amount of 2.35 billion m³ per year could be economically extracted from the Nubian aquifer compared to less than 0.07 billion m³/year from wadi Qena and wadi Hammamat in the Eastern Desert (Hefny & Shata 2004) which stretch over a larger area of about 23,500 km² (Gheith & Sultan 2002) (0.07 billion m³/year is the maximum recharge rate for the Nubian aquifer at this point, which if extracted will lead to a drop in GW levels beyond economic limits, therefore the amount that could be economically extracted is expected to be lower). Nonetheless, the Nubian aquifer in the Eastern Desert has high development potential given that the absolute maximum GW that could be extracted from the Nubian aquifer underlying main wadis north of Aswan city is estimated to be 0.21 billion m³/year (the maximum recharge rate for the Nubian aquifer at this point, which if extracted will lead to a drop in GW levels beyond economical limits), while GW extracted from the whole Eastern Desert, including the coastal aquifer, was reported to be only 0.05 billion m³/year (Hefny & Shata 2004).

The Nubian aquifer also covers the Sinai Peninsula stretching from the southern parts of the peninsula, north of the outcropping basement fissured hard rock aquifer, to the northern parts at the Gabal-El-Maghara and Gabal-El-Halal zones (Abd-El-Rahman 2003) located near the towns of Gifgaga and El-Quseima (Figure 1). The aquifer is recharged by infiltrating rainwater especially in the south where the aquifer outcrops (Abd-El-Samie & Sadek 2001), however the recharge amount is small estimated to be about 53 million m³/year (Nour & Khattab 1998). The following data on the GW properties have been obtained from RIGW (1988), Mills & Shata (1989), and Nour & Khattab (1998). The Nubian aquifer’s GW in the Sinai Peninsula is mainly brackish except in the south where the sandstone aquifer outcrops the GW is fresh (<1,000 mg l⁻¹). The GW salinity then increases gradually northward to values exceeding 10,000 mg l⁻¹ north of Gifgaga and also westward along the Suez Gulf coast where the GW is mainly saline or hyper saline with salinities as high as 220,000 mg l⁻¹ (except the Ayun-Musa area where the GW is brackish). GW in the Nubian aquifer in the Sinai Peninsula is found at large depths where the depth to top aquifer ranges from 500 to 1,100 m BGL and the depth to water table ranges from 100 to 400 m BGL (except for Ayun-Musa where the water flows above ground level). The Nubian aquifer in the Sinai Peninsula is not as productive as its counterpart in the Western Desert with reported well yields ranging from 20 to 80 m³/h. Nonetheless, the aquifer has large GW reserves with an estimated amount of 1,100 billion m³ out of which at least 117 billion m³ is available for extraction (Hefny & Shata 2004). Moreover, the aquifer has the highest development potential compared to other aquifers in the Sinai Peninsula (Nour & Khattab 1998).

**Fissured carbonate aquifer**

The fissured carbonate aquifer covers almost half of Egypt’s area (Hefny et al. 1992) and stretches over the central and northern parts of the Eastern Desert, Western Desert and the Sinai Peninsula (Figure 1). The aquifer is recharged by leaked water from the underlying Nubian aquifer through deep fractures and fissures in addition to occasional surface recharge from flash floods mainly occurring in the Eastern Desert and the Sinai Peninsula. However, the aquifer is composed of massive impervious rocks with low infiltration capacity reducing the aquifer’s recharge potential, except in areas that are highly fractured, allowing water to percolate and recharge the aquifer (Shata 1982; Gheith & Sultan 2002; Abdel-Moneim 2003). While RIGW (1988) described the fissured carbonate aquifer all over Egypt to have moderate productivities, wells tapping the aquifer in most areas were...
reported to have low productivities. Allam et al. (2003) also indicated that low amounts of GW reserves could be exploited from the carbonate aquifer, especially when compared to the large area covered by the aquifer. The aquifer is, however, not well studied (Nour & Khattab 1998, Hefny & Shata 2004) and little data on its GW potential and other GW properties were found in the literature.

In the Western Desert, the fissured carbonate aquifer’s water bearing horizons are the Upper Cretaceous and Eocene formation in addition to the Middle Miocene formation in the northern parts of the Western Desert (RIGW 1988). Data on GW properties in the fissured carbonate aquifer were mainly reported in Nour & Khattab (1998). Brackish GW exists in the Upper Cretaceous and Eocene aquifers in the Al-Qattara depression area with salinities ranging from 2,000 to 5,000 mg l⁻¹ and reaching up to 10,000 mg l⁻¹ northeast near the Mediterranean coast. The entire Middle Miocene aquifer contains brackish water with salinities ranging from 1,600 to 2,800 mg l⁻¹ in the Siwa oasis area then increasing further north reaching 10,000 mg l⁻¹ near the Mediterranean coast. No data about GW depths were found in the literature except for the Middle Miocene aquifer in the Siwa depression area where GW is found at relatively shallow depths ranging from 20 to 150 m BGL with mostly flowing GW above ground level. The Upper Cretaceous and Eocene aquifers have low well yields, i.e. <5 m³/h, while the Middle Miocene aquifer have higher yields ranging from 10 to 35 m³/h in the Siwa depression area. It is not clear, however, whether other areas in the Middle Miocene aquifer have similar moderate productivities to that of the Siwa depression area or low productivities as the Upper Cretaceous and Eocene aquifers, and no data were found in the literature on other wells tapping the aquifer in other locations.

In the Eastern Desert, scarce data were found on the fissured carbonate aquifer. The GW salinities range from 1,000 to 9,000 mg l⁻¹ but could reach 12,000 mg l⁻¹ in some areas such as Wadi-Araba, south of Ain-Sokhna. GW in the fissured carbonate aquifer in the Eastern Desert is reported to be accessed in different locations at ground surface either from springs or flowing artesian wells and the depth to top aquifer is generally shallow with values up to 100 m BGL reported in the Wadi-Araba area. Springs tapping the aquifer are also reported to have limited productivities (Hefny et al. 1992; Abdel-Moneim 2005).

In the Sinai Peninsula, the fissured carbonate aquifer consists of the Upper Cretaceous and Eocene aquifers and their GW properties are reported in Mills & Shata (1989) and Nour & Khattab (1998). GW in both aquifers is mainly brackish where the average salinity in the Eocene aquifer is estimated to be about 5,150 mg l⁻¹ while the Upper Cretaceous aquifer has lower average salinity of about 2,750 mg l⁻¹. Saline and hyper saline GW is also reported in the Eocene aquifer in the area between Ras-Sudr and Hammam-Faraon, and the area north of Al-Quseima. No data were found in the literature regarding GW depths in the Eocene aquifer while few wells tapping the Upper Cretaceous aquifer in different parts of the Sinai Peninsula have drilling depth and depth to water table ranging from 189 to 980 m BGL and 21 to 220 m BGL, respectively. The Upper Cretaceous aquifer has one of the lowest productivities compared to other aquifers in the Sinai Peninsula and is considered as an aquifer with very poor productivity and hence not recommended for future exploitation. Conversely, the Eocene aquifer is reported to have a moderate productivity with values close to that of the Nubian aquifer in this area. However, there is an uncertainty about the Eocene aquifer’s productivity as scarce data were found in the literature on wells tapping this aquifer.

**Quaternary aquifer**

The Quaternary aquifer is divided into several hydrogeological systems that are different in lithology, recharge resources and productivity (RIGW 1988). The Quaternary aquifer includes the Nile basin aquifer and the alluvial deposits aquifer which mainly exists in the Eastern Desert and the Sinai Peninsula. The Quaternary aquifer is also part of the Red Sea and Suez Gulf coastal aquifers, which are discussed separately.

**Nile basin aquifer**

The Nile basin aquifer covers all the area along the Nile River basin underlying the cultivated lands (Idris & Nour 1990). The aquifer mainly consists of the Quaternary
Pleistocene epoch sand and gravel aquifer. The Pleistocene aquifer is overlain by a silt and clay cap belonging to the Holocene epoch which acts as a semi confining layer. The silt and clay cap disappears in the desert fringes where the aquifer becomes unconfined (Idris & Nour 1990; Abdalla et al. 2009). The Nile basin aquifer is continuously recharged by water leaking from irrigation canals and drains as well as water leaching from excess irrigation water (Idris & Nour 1990). Therefore, the aquifer is a renewable source of GW and is considered by RIGW (1988) as the most productive aquifer in Egypt except in the northern areas where the large thickness of the impervious clay lenses reduces the aquifer’s productivity. Infiltrating rainfall also recharges the aquifer in the Nile delta area mainly in the unconfined zone particularly in winter where rainfall ranges from 25 mm in the south to 200 mm per year in the north near the Mediterranean Sea (Geirnaert & Laeven 1992). The aquifer is separated into the Nile Delta aquifer and the Nile Valley aquifer as the thickness of the Nile basin aquifer decreases from south to north near Cairo where it becomes very thin, then increases again further north, forming the Nile Delta aquifer (Hefny et al. 1992).

The Nile Valley aquifer stretches in the vicinity of the Nile River from Cairo in the north to Aswan southward (Figure 1). Its GW is mainly fresh with an average salinity of 800 mg l\(^{-1}\) (Hefny et al. 1992) although brackish GW might be found at the fringes of the Nile valley where some wells analysed by Abdalla et al. (2009) in Qena area have GW salinities with values up to 3,000 mg l\(^{-1}\). The fresh GW zone in the Nile basin aquifer is, however, polluted and will require treatment to be suitable for drinking. According to Abdel-Lah & Shamrukh (2001), Abdalla et al. (2009), Abdel-Latif & El-Kashouty (2010) and Ahmed & Ali (2011), Escherichia coli bacteria and high levels of nitrate and iron were detected in many wells due to leaking sewage systems and septic tanks, mainly used in rural areas, and the excessive use of fertilizers.

The Nile Delta aquifer stretches east to the Suez Canal, north to the Mediterranean Sea and south to Cairo. Westward, the aquifer is bordered by the Al-Moghra and the fissured carbonate aquifers. Its GW is fresh in the southern and central parts of the delta but the GW salinity increases eastward and northward to become brackish and saline due to salt water intrusion from the Mediterranean Sea and the northern saline lakes. GW salinity also increases westward due to its contact with the Al-Moghra aquifer (Hefny et al. 1992; Sharaky et al. 2007). The area containing brackish GW was identified based on the study by Sherif et al. (2012). The GW salinity maps in the study, which were based on simulation work and field observations, included the variation of salinity within a depth ranging from zero to 400 m below mean sea level. However, we only included the data for depths of zero and 100 m below mean sea level as this is where brackish GW mainly exists. It should be noted that in the transition areas between fresh/brackish and brackish/saline GW, fresh and brackish GW, respectively, might be only found at very shallow depths and within a very thin zone in the range of few meters and therefore the available GW quantities could be small. The GW salinity data were complemented from the iso-salinity map by Geirnaert & Laeven (1992) for the western fringes although the study did not consider the variation of salinity with depth. However, the fresh/brackish and the brackish/saline iso-salinity boundary lines agree well with those of Sherif et al. (2012) for the rest of the Nile Delta aquifer. It should be noted that while the study by Sherif et al. (2012) showed that all of the northern parts of the Nile Delta aquifer contains saline water, a study by Ebraheem et al. (1997) to determine the fresh/brackish/saline zone location and thickness showed that brackish GW also exists in the middle part of the northern delta but with a small thickness of about 60 m and is underlain by saline GW. Hefny & Shata (2004) also mentioned the presence of brackish GW in the northern delta at depths less than 100 m. However, based on field observations it is likely that only small volumes of brackish, as well as fresh, GW exist in this area (M. Sherif, 2013, pers. comm., 28 Nov.); accordingly we considered the whole northern delta to contain saline water. The study by Ebraheem et al. (1997) also showed that a thin zone, around 20 m in thickness, of brackish GW overlies the fresh GW zone in the middle area south of the 1,000 mg l\(^{-1}\) iso-salinity line, whose presence is attributed to salt leaching from irrigation water return. Regarding GW depths, the depth to top aquifer in the confined area of the Nile Delta aquifer is very shallow ranging from zero to 30 m BGL and the depth to water table ranges from zero (flowing wells) to few meters (<5 m) (RIGW 1988; Dawoud et al. 2005; Sherif et al. 2012). In the unconfined
areas in the western delta, the depth to water table and well depths are also shallow ranging from 55 to 60 m BGL and 40 to 80 m BGL, respectively (Sharaky et al. 2007).

Quaternary alluvial deposits aquifer

The Quaternary alluvial deposits aquifer mainly covers wadi floors in the Eastern Desert and the Sinai Peninsula. The aquifer is renewable and has a high storage capacity and infiltration rates which increases its surface recharge potential (Gheith & Sultan 2002, Abdel-Moneim 2005).

In the Western Desert, the Quaternary alluvial deposits only exist in some areas along the Nile River’s desert fringes and in the Siwa oasis area. Scarce data were found in the literature on the alluvial deposits aquifer in the former, but Hefny et al. (1992) reported that the aquifer in the western and eastern desert fringes in general has GW salinities ranging from 500 to 3,000 mg l$^{-1}$. In the Siwa oasis area, the Quaternary alluvial deposits aquifer is recharged from return irrigation water and from the uncontrolled flow of GW from wells tapping the Middle Miocene aquifer in addition to upward leakage of GW from the underlying carbonate aquifer. GW salinities in the Quaternary aquifer in this area are high ranging from 5,000 up to 40,000 mg l$^{-1}$ near the salt lakes while the depth to water table is very shallow ranging from 1 to 5 m BGL (Nour & Khattab 1998).

In the Eastern Desert, the Quaternary alluvial deposits aquifer is the most important shallow GW supply in this area (Abdel-Moneim 2005) and also has good potential for sustainable extraction (Sultan et al. 2000, 2002). Several wells analysed by Sultan et al. (2000) and Sturchio et al. (2005) in different wadis in the Eastern Desert showed that the GW is mainly brackish with salinities reaching up to around 5,500 mg l$^{-1}$ but some wells contain fresh GW. The depth to water table ranges from 31 to 65 m BGL (Sultan et al. 2007). The aquifer is renewable and mainly recharged by flash floods surface runoff, where rainwater over the Red Sea hills is channelled through the wadis towards the Nile valley, with an amount estimated to be from 2.9 to 54.1 million m$^3$/year (Milewski et al. 2009). The aquifer in this area is reported by RIGW (1988) to have lower productivities than other rainfall recharged aquifers such as the Mediterranean coastal aquifer. Nonetheless, Sultan et al. (2007) showed that the thick alluvium Quaternary aquifer in wadi Asyuti is recharged by ascending Nubian GW through deep seated faults, which increases its potential for GW extraction (Sturchio et al. 2005) and its productivity. Sultan et al. (2007) reported that wells in this area have moderate to high well yields ranging from 50 to 100 m$^3$/h. The authors also identified other localities within the Nile flood plain and along the Suez Gulf and Red Sea coast that are potentially recharged by ascending Nubian GW and therefore are also likely to have moderate to high productivities.

The Quaternary alluvial deposits aquifer in the Sinai Peninsula is recharged by flash floods surface runoff channelled through main wadis draining towards the Mediterranean Sea and both the Al-Aqaba and Suez gulfs (Gheith & Sultan 2001). Scarce data were found in the literature regarding GW salinities, but according to Mills & Shata (1989) the Quaternary aquifer in the coastal areas and main wadis mainly contains brackish GW with an average salinity of 2,300 mg l$^{-1}$. The depth to the water table is shallow, ranging from 3.5 to 45 m BGL (El-Fiky 2010; Elewa & Qaddah 2011). The aquifer receives much higher rainfall recharge than its counterpart in the Eastern Desert. According to Milewski et al. (2009), the alluvial deposits aquifer in wadi Al-Arish watershed, which stretches from Al-Arish city to the central parts of the Sinai Peninsula and encompasses most of alluvial deposits aquifers in the Sinai Peninsula, is annually recharged by an estimated amount of 581.6 million m$^3$/year. Assuming that, based on the geological map by Milewski et al. (2009), roughly 50% of the wadi Al-Arish watershed is covered by alluvial deposits, the amount of rainfall recharge per unit area is at least 2.5 times higher than the alluvial deposits aquifers in the main wadis in the Eastern Desert. Therefore, while RIGW (1988) described the alluvial deposits aquifer in the Sinai Peninsula to be low to moderately productive and receiving insignificant rainfall recharge similar to its counterpart in the Eastern Desert, we concluded that the Quaternary alluvial deposits in the Sinai Peninsula is likely to be more productive.

Coastal aquifers

The coastal aquifers cover coastal areas along the Mediterranean Sea and the Red Sea, in addition to the Suez Gulf and
the Suez Canal (Figure 1). The coastal aquifer along the Mediterranean coast includes the North Sinai coastal area, the North West Mediterranean coastal area and the northern delta area which is part of the previously discussed Nile Delta aquifer.

The North West Mediterranean coastal aquifer stretches from Alexandria city to Egypt's western borders. According to Hefny & Shata (2004) and Atta et al. (2005), the aquifer belongs to the Quaternary age and is recharged by: rainfall which could reach 200 mm/year; lateral seepage from the Nile Delta aquifer; excess irrigation water especially in the Maryut area where a large area is cultivated; and seepage from irrigation canals transporting Nile water to west Alexandria. The coastal aquifer in the North West Mediterranean area mainly contains brackish water with salinities ranging from 1,000 to 6,000 mg l$^{-1}$ and the GW is found at shallow depths where the depth to water table is 15 m BGL on average. The aquifer in this area receives a high amount of rainfall recharge and is described as a moderately to highly productive aquifer (RIGW 1988). The aquifer in this area is also heavily underutilized where only 10% of its estimated 50 million m$^3$/year of exploitable GW is extracted (Hefny & Shata 2004).

The Red Sea coastal aquifer mainly consists of the Miocene sandstone aquifer and the Quaternary alluvial deposits aquifer where the latter exists in the deltaic areas of the main wadis in the coastal plains (Abdel-Moneim 2005). The Nubian aquifer is also found along the Red Sea coast but it mainly exists at large depths reaching 3 km BGL (Sultan et al. 2007) while in the area where the aquifer outcrops the GW is likely to be saline based on the aquifer’s fresh/saline GW boundary line. The Quaternary and the Miocene aquifers are recharged by infiltrating surface runoff water from flash floods. However, according to RIGW (1988) they receive an insignificant amount of surface recharge compared to the Mediterranean coastal aquifer and therefore are considered to have a lower productivity except in the extreme southern parts where the aquifers receive higher amount of surface recharge and have a moderate to high productivity, which is because the amount of precipitation in this area is high (Abdel-Moneim 2005). Nonetheless, while RIGW (1988) described the coastal aquifers’ productivity and surface recharge in the extreme southern parts of the Red Sea to be similar to that of the Mediterranean coast, they are expected to be lower as the amount of precipitation in the former is in the range of 35 to 60 mm/year compared to at least 75 mm/year in the latter based on the precipitation map shown in (Milewski et al. 2009). The precipitation map also shows that the Red Sea coastal area at Suez city has a high precipitation rate similar to that of the extreme southern parts and therefore the coastal aquifer in this area is likely to have similar productivities. Moreover, the area extending from Hurghada to Ras-Ghareb city was identified by Sultan et al. (2007) to be a potential discharge area for the Nubian aquifer and therefore the Quaternary aquifer could have higher productivities. Regarding GW properties, water salinity data in the Quaternary aquifer could be only found in the Al-Quseir/Safaga area where the salinities range from 1,500 to 9,500 mg l$^{-1}$ (Awad et al. 1996). In general, the Quaternary alluvial deposits aquifer contains brackish GW and with relatively higher salinities than its counterpart near the Nile valley which is attributed to seawater intrusion (Abdel-Moneim 2005). GW in the Miocene aquifer is also brackish with salinities ranging from 2,000 to 2,500 mg l$^{-1}$ (Hefny et al. 1992). Hefny et al. (1992) also reported that GW in the Quaternary aquifer is shallow where the alluvial deposits are found at depths ranging from 1 to 15 m. For the Miocene aquifer, scarce data were found regarding GW depths, however it is likely to be shallow as the aquifer outcrops in many locations and also the depth to water table of two artesian wells analysed by Awad et al. (1996) in the Al-Quseir/Safaga area is only 12 m BGL in both wells while the drilling depths are 12 and 78 m BGL. The Red Sea coastal aquifer has a high development potential as out of the estimated 31 million m$^3$/year of GW that is available for extraction from the aquifer, only 5 million m$^3$/year was reported to be extracted from the entire Eastern Desert which includes other aquifers (Hefny & Shata 2004).

The coastal aquifer in the Sinai Peninsula consists of the Quaternary and Miocene sandstone aquifers. Both aquifers are recharged by local rainfall in the northern coastal area, which could reach values as high as 300 mm/year at Rafah city (Abd-El-Samie & Sadek 2001), and flash floods over the Sinai hills channelled towards main wadis and draining towards the Mediterranean Sea and the Al-Aqaba and Suez gults (Gheith & Sultan 2001; Allam et al. 2005). The Quaternary aquifer in the northern coastal area is also
recharged from return imported Nile water (Abdallah 2006). According to RIGW (1988), the Quaternary aquifer is moderately to highly productive along the Mediterranean coast and most of the Al-Qaa plain along the Suez Gulf which is supported by well yield data reported in Mills & Shata (1989) with values up to 65 and 115 m³/h in the Al-Arish area and the Al-Qaa plain respectively. The Miocene sandstone and the Quaternary aquifer in other areas along the Suez Gulf is described by RIGW (1988) to have low to moderate productivities and to be limitedly recharged by rainfall similar to its counterpart in the Eastern Desert. Nonetheless, as the Sinai Peninsula receives higher rainfall than the Eastern Desert and according to Mills & Shata (1989) wells tapping the Miocene and the Quaternary aquifer in general have the highest productivities in the Sinai Peninsula, we concluded that the coastal aquifer in the Sinai Peninsula is likely to be more productive than its counterpart in the Eastern Desert. The Suez Gulf coastal aquifer has also high development potential as the GW is heavily underutilized where only 10% of the Suez Gulf coastal aquifer’s annual rainfall recharge rate is extracted (Hefny & Shata 2004).

The following data on GW properties have been obtained from RIGW (1988), Mills & Shata (1989), Hefny & Shata (2004), Abdallah (2006), and Elewa & Qaddafi (2011). GW in the Quaternary coastal aquifer is mainly brackish (1,000–10,000 mg l⁻¹) but fresh GW exists in some areas in the Al-Qaa plain and Rafaf area while saline GW is reported south of the Al-Bardaweel Lake and the northern corner of the North Sinai coastal aquifer. The Miocene aquifer’s GW is also mainly brackish but more saline than the Quaternary aquifer with an average salinity of 5,500 mg l⁻¹. Saline and hyper saline GW with salinities ranging from 27,200 to 84,700 mg l⁻¹ are also reported in the Miocene aquifer in the area between Ras-Sudr and Hammam-Faraon. The depth to water table in the Quaternary aquifer in northern Sinai is less than 15 m BGL while it can reach 70 m in the Al-Qaa plain and it ranges from 16 to 45 m BGL in the Miocene sandstone aquifer.

**Basement fissured hard rock aquifer**

The basement fissured hard rock aquifer belongs to the Pre-Cambrian Supereon and mainly outcrops in the mountainous area of the Eastern Desert and south of the Sinai Peninsula. GW in this aquifer is limited to areas where the rocks contain cracks and fractures acting as a water bearing zone where rainfall is the only source of recharge (Sturchio et al. 2005). In the Eastern Desert, GW in the Pre-Cambrian aquifer varies from fresh to brackish with salinities up to 3,500 mg l⁻¹ (Abdel-Moneim 2005). The depth to water table and the drilling depth of some wells, reported in the literature (Awad et al. 1997; Sultan et al. 2007) range from 5 to 30 m BGL and 6.4 to 38.2 m BGL respectively. In the Sinai Peninsula, the Pre-Cambrian GW also exists at shallow depth (<50 m) and has low salinities ranging from 1,000 to 2,000 mg l⁻¹ (RIGW 1988) although GW with salinities up to 5,123 mg l⁻¹ are reported (Hefny & Shata 2004). The aquifer also contains fresh GW (<1,000 mg l⁻¹) especially in the Saint Catherine area (Tantawi et al. 1998). According to Hefny & Shata (2004), the aquifer has very limited potential for sustainable GW extraction because it is limitedly recharged by the occasional rainfall over mountainous areas due to its hard rock composition which has negligible porosity increasing surface run off potential. The authors have also reported that most springs tapping the aquifer have very limited productivity.

**Al-Moghra aquifer**

The Al-Moghra aquifer belongs to the Lower Miocene age and is located in the Western Desert stretching from west of the Nile delta to, and encompassing most of, the Al-Qattara depression in the west covering an area of 50,000 km² (Dawoud et al. 2005). The aquifer contains fossil water, which came from an old Nile delta that existed in this location millions of years ago (Allam et al. 2003). The following data on the aquifer’s sources of recharge and GW properties were obtained from Rizk & Davis (1991), Hefny et al. (1992), Nour & Khattab (1998) and Hefny & Shata (2004). The Al-Moghra aquifer is recharged from several sources: lateral seepage from the Nile Delta aquifer in the east with an estimated amount of 50 to 100 million m³/year; direct rainfall on the aquifer’s outcrops with an estimated amount of 100 million m³/year; leaking water from the underlying Nubian aquifer through cracks particularly in its southern parts by an amount preliminary estimated to be 1 billion m³/year; seepage from the overlying Middle Miocene aquifer in the west; and Mediterranean seawater from...
the north. The Al-Moghra aquifer’s GW is mainly brackish (1,000–10,000 mg l\(^{-1}\)) except some areas in the east close to the recharge areas from the Nile delta where the aquifer contains fresh GW with salinities as low as 350 mg l\(^{-1}\). Salinities as high as 15,000 mg l\(^{-1}\) are also reported in the northern parts of the aquifer near the Mediterranean coast. GW in the Al-Moghra aquifer is shallow to moderately deep where the depth to top aquifer ranges from zero to 200 m BGL; and, based on a piezometric contour map of the aquifer and drainage basin, the depth to water table ranges from zero, especially in the central areas of the aquifer and up to 290 and 350 m BGL in some locations in the north western and south eastern parts, respectively. The aquifer could have a promising potential for GW extraction due to its large GW stored volume that could reach 10,000 billion m\(^3\) (Hefny & Shata 2004) and because the aquifer partially receives renewable water. However, according to Allam et al. (2003) there is no estimation of the exploitable GW from the aquifer. No data regarding well yields were found in the literature but the aquifer has been generally described by RIGW (1988) as a low to moderately productive aquifer.

The Pliocene epoch aquifer is another important aquifer that is sometimes associated with the Al-Moghra aquifer (Allam et al. 2003). The aquifer is recharged through lateral seepage from the Nile Delta aquifer, upward leakage from the Al-Moghra aquifer and drainage water from the Al-Nubareya reclamation project in the western delta (Hamza et al. 1984; El-Kashouty & El-Sabbagh 2011). The Pliocene aquifer is described by RIGW (1988) to be a moderately to highly productive aquifer which is likely due to its closeness to the recharge areas in the Nile delta. The aquifer mainly contains brackish GW with salinities up to 5,000 mg l\(^{-1}\) (Ammar 2010) but also contains fresh GW especially in the southern and eastern parts close to the recharge area from the Nile Delta aquifer (Sharaky et al. 2007). GW depth in the Pliocene aquifer is mainly shallow where the drilling depths of several wells tapping the aquifer are reported to range from 23 to 119 m BGL (Idris & Nour 1990).

### Classification of brackish water aquifers

Aquifers in Egypt were classified for their potential for sustainable brackish GW extraction based on their productivity, renewability, GW depth and development potential. A multi-criteria analysis was used to rank brackish GW aquifers in the six main regions in Egypt and those having similar scores were assigned a similar rank.

The aquifer’s productivity determines the size of the supported decentralized community which is important as the established decentralized community should produce enough revenue exceeding the costs of extracting GW (Hefny & Shata 2004), therefore it was given the highest weight (Table 2). Productivity was divided into five classes ranging from low to high, where the highest rank was given to aquifers described by RIGW (1988) to have very high productivity as well as aquifers with reported well yields exceeding 150 m\(^3\)/h.

Surface recharge reflects the potential for long term extraction hence the sustainability of GW extraction. Sustainability is important to justify the high cost of the infrastructure required to establish decentralized communities (Lamoreaux et al. 1985). Extracting non-renewable GW leads to continuing decrease in GW levels, such as in the oases area in the Western Desert where many wells tapping the Nubian aquifer ceased to flow naturally due to heavy extraction and digging closely spaced wells (Shata 1982; Sultan et al. 2007), which increases water lifting costs and compromises the sustainability of the community relying on the GW. On the contrary, extracting GW from a

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Weights and ranks of factors used to assess the aquifers’ potential for brackish GW extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Weight</td>
</tr>
<tr>
<td>Productivity</td>
<td>75%</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewability</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater Depth</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
renewable aquifer should not lead to a drop in water levels as long as GW extraction rates do not exceed the surface recharge rates. A renewability factor was therefore used to differentiate between renewable and non-renewable aquifers and was given a weight of 10% (Table 2). The renewability factor was divided into three classes: renewable aquifers which are mainly recharged from surface water; partially renewable aquifers which contain fossil water and are also renewed by surface water; and non-renewable aquifers which mainly contain fossil water with insignificant surface recharge.

GW depth determines the water lifting and drilling costs. The GW depth factor was divided into five main classes ranging from shallow to deep. Aquifers with depths to water table and depths to GW less than 100 m BGL were classified as shallow aquifers while aquifers with depth to water table and depth to GW exceeding 200 and 500 m, respectively, were classified as deep aquifers. Confined aquifers with shallow water tables and deep depth to GW were assigned to the moderate GW depth class. Depth to GW is the depth at which GW is found and reflects the drilling depth required. The depth to GW was determined either from well depth or depth to top aquifer data available in the literature. The depth to water table represents the actual water level in the well casing which determines the dynamic head required for water lifting and may differ from the depth to GW in confined aquifers.

Finally, aquifers with low development potential (as further extraction is not recommended because the maximum amount of exploitable GW is either reached or exceeded) were assigned to the lowest class regardless of their productivity, renewability and depth to GW.

The results of the classification are presented in Table 3, Figures 2 and 3. Each area’s potential for brackish GW extraction was determined based on the highest class aquifer as more than one aquifer may exist in the same area at different depths. It should be noted however, that shallow/outcropping aquifers that have lower potential compared to the underlying aquifer could still be attractive for brackish GW extraction due to fewer costs of drilling wells and water lifting, provided that sufficient GW is available to sustainably meet the demand of the decentralized community. All aquifers existing at depths greater than 1 km BGL were not considered for brackish GW extraction due to the high cost of extracting water.

Constraints limiting GW development

There are several hazards that may limit brackish GW development and the establishment of decentralized communities away from the Nile valley and delta area. Sand drift is reported to constrain the development of cultivated lands and to cause damage to infrastructure such as houses, roads, irrigation canals and drains (Philip et al. 2004; El-Gammal & El-Gammal 2010; Hereher 2010). Locations of sand dunes and other aeolian forms were identified from a study by Misak & Draz (1997). The study shows that approximately 18% of Egypt's area is covered by sand dunes and are mostly (93%) concentrated in the Western Desert. Sand drift hazard can however be combated by preserving natural vegetation, planting drought resistant trees and shrubs to break wind force, and mechanical stabilization of sands either through chemicals or through mulching, which is covering sand dunes with sheets made of synthetic and dry plant materials (Misak & Draz 1997).

Flash floods are another constraint and mainly affect the Eastern Desert and the Sinai Peninsula causing damage to roads and residential areas (El-Fiky 2010). For example, in 2010 flash floods affecting both areas caused some deaths as well as injuring and displacing hundreds of people in addition to roads and infrastructure damage (International Federation of Red Cross and Red Crescent Societies 2010). For this reason, in the study by Salim (2011) to assess different sites’ suitability for solar driven GW extraction, most flash-flood prone areas were excluded. However, flash-flood prone areas offer an opportunity to exploit this otherwise wasted water through the use of small dams across flood ways, settling tanks and trenches to recharge the underlying aquifers, as discussed in Sonbol (2009) and Masoud (2011), hence increasing their potential for sustainable extraction.

The presence of landmines, in addition to unexploded ordnances (UXO), is another hazard that may limit GW extraction and development in Egypt because of the extra costs required for their clearance. The presence of landmines and UXO, mainly from the Second World War, has affected and impeded the development of agricultural,
touristic and irrigation projects (Trevelyan 2000; Abdel-Kader & Yacoub 2005; Hoelzgen 2008; International Campaign to Ban Landmines 2010; Egypt State Information Service 2011). Studies by Trevelyan (2000), Said (2003) and Abdel-Kader & Yacoub (2005) were used to identify areas affected by landmines and UXO. However, most studies reported that the available minefield records and maps are limited, lost, inaccurate or incomplete and the existence of UXO is usually not covered as it extends over a large area (Trevelyan 2000; Said 2003; Abdel-Kader & Yacoub 2005; 

<table>
<thead>
<tr>
<th>Aquifer ranking</th>
<th>Productivity</th>
<th>Renewability</th>
<th>Groundwater depth</th>
<th>Percentage of Egypt’s area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class I (Highest Potential)</td>
<td>High</td>
<td>Renewable</td>
<td>Shallow</td>
<td>0.8% (Approx. area: 7,480 km²)</td>
</tr>
<tr>
<td>II</td>
<td>Moderate to High</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td>Moderate to Deep drilling depth &amp; shallow depth to water table</td>
</tr>
<tr>
<td></td>
<td>Moderate to High</td>
<td>Partially Renewable</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Moderate</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td>Moderate to Deep drilling depth with shallow depth to water table</td>
</tr>
<tr>
<td></td>
<td>Moderately to High</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Moderate to High</td>
<td>Partially Renewable</td>
<td>Shallow</td>
<td>Deep to Moderate</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low to Moderate</td>
<td>Partially Renewable</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Low</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td></td>
</tr>
<tr>
<td>Partially Renewable or Renewable</td>
<td>Shallow</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partially Renewable or Renewable</td>
<td>Deep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>Non Renewable</td>
<td>Shallow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class V also includes aquifers where further extraction is not recommended as the maximum amount of exploitable GW is either reached or exceeded</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V-III/Lack of Data</td>
<td>Low or Moderate productivity. Uncertainty due to lack of data in the literature</td>
<td>Non Renewable in the Western Desert Partially renewable or renewable in the Eastern Desert and the Sinai Peninsula</td>
<td>Shallow except in the Sinai Peninsula where depths are Moderate to Deep</td>
<td>6.6% (Approx. area: 65,520 km²)</td>
</tr>
<tr>
<td>Saline Groundwater</td>
<td>Aquifers mainly containing GW with salinities &gt; 10,000 mg/l</td>
<td>1.1% (Approx. area: 11,220 km²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Groundwater</td>
<td>Includes all aquicludes where there are no available data on the underlying aquifer in addition to aquifers which are likely to contain no GW due to absence of recharge resources</td>
<td>1.3% (13,380 km²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh Groundwater</td>
<td>GW with salinities &lt; 1,000 mg/l not exposed to pollution</td>
<td>40.3% (Approx. area: 399,870 km²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fresh Polluted Groundwater</td>
<td>GW with salinities &lt; 1,000 mg/l which are polluted with pathogens, nutrients and trace elements caused by anthropological activities</td>
<td>2.5% (Approx. area: 24,450 km²)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2 | Aquifers’ potential for brackish GW extraction.
Megahed et al. (2010). In addition, as all available maps are before 2000, while land landmines and UXO clearance activities had been carried out until at least 2009 (Megahed et al. 2010; Abdel-Mohsen 2011) the identified locations are likely to be overestimated. Therefore, while we excluded some areas that are already developed, the locations identified will only be indicative of areas that are potentially affected.

Figure 3 | Aquifers’ potential for brackish GW extraction in the Sinai Peninsula. Base map modified after Elewa & Qaddah (2011).
DISCUSSION

Brackish GW with the potential for sustainable development for decentralized agricultural communities was assessed in the six main regions in Egypt which are: the Western Desert, the Eastern Desert, Nile valley and delta, the Sinai Peninsula, the Mediterranean and the Red Sea coastal areas.

Western Desert

The Western Desert occupies approximately 69% of Egypt’s area (approx. 684,100 km²) and has a great potential for brackish GW extraction. One fifth of the Western Desert’s area has access to brackish GW from the Nubian aquifer which has large GW reserves and was considered as a class II aquifer due to its high productivity and high development potential in this region. In addition, while the Nubian aquifer is a deep aquifer system, thereby increasing drilling costs, GW in most wells flows to the surface which decreases water lifting costs.

Almost 60% of the Western Desert’s area, however, contains fresh GW found in the Nubian aquifer (Figure 2) and therefore the priority for establishing decentralized communities based on GW extraction should be given to this area as only simple GW treatment will be required. GW treatment is required in the fresh GW zone of the Western Desert due to high concentrations of iron and manganese (Gossel et al. n.d.; Hamza et al. 2000; El Tahlawi et al. 2008) exceeding the World Health Organization guidelines (World Health Organization 2011). Nonetheless, given that the brackish GW zone in the Western Desert mainly occurs along the Nile River, establishing decentralized communities in this area would be more attractive due to its closeness to the Nile valley and, therefore, less investment will be required for providing the infrastructure needed to attract new immigrants (Lamoreaux et al. 1985) such as healthcare and educational services. For example, according to Lonergan & Wolf (2001), developing fresh water resources in areas close to major populated areas in Egypt, such as the Al-Nubareya canal, was more successful in attracting new families as opposed to isolated projects in the deserts such as the Toshka project in the New Valley area in the Western Desert where farmers temporarily move to work without settling due to lack of infrastructure. The brackish GW zone is also less exposed to sand drift hazards opposed to the fresh GW zone where around 85% of sand dunes in the Western Desert are concentrated. Furthermore, most of the brackish GW zone along the Nile River has high potential for brackish GW extraction (Class II) as it has access to the Nubian aquifer in addition to the shallow Quaternary aquifer which in some areas has high potential for GW extraction as it is likely to be a discharge area of the Nubian aquifer.

In the northern parts of the Western Desert, the Nubian aquifer exists at great depths (>1 km BGL) and is mostly saline and therefore is not economical for extraction. Brackish GW could be extracted from the lower potential Miocene aquifer and the Al-Moghra aquifers which outcrop in this area. Nonetheless, the northern part of the Western Desert may not be suitable for establishing decentralized communities due to its remoteness. Moreover, the northern area east of the Al-Qattara depression is exposed to sand drift hazard and many areas near the Mediterranean coast are likely to be affected by landmines and UXO. Furthermore, according to Masoud & Koike (2006), as Al-Qattara is a depression area with an extremely arid climate, irrigation water demand as well as soil salinization will increase due to high evaporation rates, which will constrain the development of agricultural communities. Brackish GW extraction and desalination would be, however, ideal to supply water for the oil and gas exploration companies concentrated in this remote area (Oil&Gas 2012), instead of transporting fresh GW with trucks which can be expensive.

The Siwa depression is another important area for brackish GW extraction. The area is an important site for agricultural development, the main activity in this area (Masoud & Koike 2006; El-Naggar 2010), and due to its remoteness, water demand is met through GW extracted from the brackish Middle Miocene aquifer and the fresh Nubian aquifer. While the priority for GW extraction should be given to the Nubian aquifer as it contains fresh water, most agricultural water demand in the past was met through brackish GW from the Middle Miocene aquifer (Nour & Khattab 1998) as its water is naturally discharged in springs or exists at shallow depths hence can be accessed through cheaply hand-dug wells. While there are no recent
data in the literature regarding GW extracted from each aquifer, it is likely that agricultural water demand is still, and will continue to be, mainly met from the Middle Miocene aquifer due to its shallowness, while GW extracted from the Nubian aquifer is likely to be reserved for domestic purposes. It should be noted that the cultivated zone of the Siwa depression area is reported to suffer from soil salinization caused by water logging due to improper drainage systems, overuse of water in irrigation and the uncontrollable discharge of the natural flowing wells (Masoud & Koike 2006; EI-Naggar 2010), therefore further use of brackish GW directly in irrigation will exacerbate soil salinization. Accordingly, desalinating the naturally flowing brackish GW from the Middle Miocene aquifer might be a necessity to avoid further soil salinization and also to make use of this wasted resource which is otherwise causing water logging problems. Extracting brackish GW from the Quaternary aquifer is also recommended to lower the water table in this area hence avoiding further soil salinization problems.

Finally, as all aquifers in the Western Desert are non-renewable, studies are required to determine the maximum withdrawal rate and the duration at which extracting GW would still be economical despite increasing water lifting costs.

**Eastern Desert**

The Eastern Desert occupies 19% of Egypt’s area and is an important area for brackish GW extraction as 98.7% of the area has access to brackish GW. However, the Eastern Desert has a lower potential for brackish GW extraction compared to the Western Desert as approximately 60% of the area is covered by the low productive Pre-Cambrian and carbonate aquifers (Figure 2). Nonetheless, the Eastern Desert receives relatively high amounts of rainfall, which mainly recharges the shallow Quaternary aquifer, increasing its potential for sustainable extraction compared with the Western Desert whose GW is mainly non-renewable. Furthermore, the Eastern Desert is bordered by the populated areas all over the Nile valley and the reasonably populated Red Sea coastal cities, such as Suez, which allows a gradual expansion of decentralized communities.

The Quaternary aquifer in wadi Qena, Hammamat and Asyut, has the highest potential for brackish GW extraction (Class II) in the Eastern Desert as the aquifer is recharged by rainfall and is also likely to be recharged by ascending Nubian GW hence the GW could be produced sustainably and with high productivities. Therefore, priority for brackish GW extraction and establishing decentralized communities should be given to the shallow Quaternary aquifer in those wadis due to their high brackish GW potential and also their closeness to populated areas.

The second priority should be given to the Nubian aquifer which covers one third of the Eastern Desert and has similar productivities as the Class II shallow Quaternary aquifers in the Eastern Desert. However, due to its non-renewability and higher depths to GW, the aquifer was considered to have a lower potential (class III) for brackish GW extraction. Both areas where the Quaternary and the Nubian aquifer are accessed are also relatively plain compared to the rigorous mountainous area of the Precambrian basement complex and therefore are more suitable for establishing new communities.

The whole Eastern Desert is, however, exposed to flash floods given that most of the Eastern Desert is covered by impervious limestone rocks which have low infiltration capacity. Abdel-Moneim (2005) classified the main wadis in the Eastern Desert based on their infiltration capacity and most of the wadis were shown to have poor recharge potential and therefore high probability of experiencing flash floods. Nonetheless, with proper measures flash floods offer an opportunity to increase shallow aquifers’ recharge, hence their potential for GW extraction.

**Sinai Peninsula**

The Sinai Peninsula occupies approximately 6% of Egypt’s area and is experiencing water shortages (Rayan et al. 2001) which hinders development efforts especially in the area that has a high potential for tourism, agricultural, industrial and mining activities (Abd-El-Samie & Sadek 2001). According to Rayan et al. (2001) and Elewa & Qaddah (2011), the current water demand in the Sinai Peninsula is met by seawater desalination and GW extraction mainly in the north eastern Mediterranean coastal area. Drinking water is also transported by trucks in areas that are not...
connected to the water distribution network. The Al-Salam Canal which transports Nile water to be used in irrigation is another main source of water in the Sinai Peninsula. However, it has an unreliable water supply with reported water shortages in the canal and high salinity of the transported water (Abdallah 2012). Therefore, given that approximately 85% of the Sinai Peninsula area has access to brackish GW aquifers, decentralized brackish GW extraction and desalination could be more economical and reliable to meet the water demand in this area. A local water supply would also save in costs associated with transporting water by trucks.

Approximately 68% of the Sinai Peninsula has access to aquifers with moderate to high potential for brackish GW extraction (Class IV to II) (Figure 3). The coastal and the alluvial deposits of the Quaternary aquifers have the highest potential due to the large amounts of rainfall in the Sinai Peninsula that recharges the aquifers especially the areas along the Mediterranean coast and in the Al-Qaa plain. However, some areas in North Sinai with access to the Quaternary aquifer are exposed to sand drift hazard and many parts are likely to contain landmines and UXO which will constrain the development of new communities. Therefore, priority for establishing decentralized communities based on brackish GW extraction and desalination should be given to the area accessing the Quaternary aquifer in the central parts of the peninsula. Further brackish GW extraction is also not possible from the Quaternary aquifer in the north eastern Mediterranean coastal area as GW extraction has already exceeded the annual rainfall recharge (Hefny & Shata 2004) as it is heavily used to meet domestic and agricultural water needs. It should be noted, however, that brackish GW desalination is strongly required in this area as the GW is mostly brackish and, based on the chemical analysis carried by El-Alfy (2012), is heavily polluted and therefore is not suitable for human consumption and is, according to Kaiser & Greish (2007), associated with the widespread of diseases such as diarrhoea and kidney diseases in the area.

The Nubian aquifer is also an important aquifer for brackish GW extraction and has the highest development potential in the peninsula. The Nubian aquifer in this area has large GW reserves and it contains brackish GW within a significant area of the peninsula (27%) particularly in the central parts. However, the main limitation for GW extraction from the aquifer is the large depths at which GW is found, which is the largest in Egypt in terms of drilling depths and depth to water table. Therefore, areas accessing the Nubian aquifer should have the second priority for brackish GW development. It should be noted that the Eocene aquifer which overlies the Nubian aquifer in many locations in the Sinai Peninsula may have more potential than the latter as it was reported to have a similar productivity but with shallower GW depths and therefore would be more attractive for brackish GW extraction; however little data on the aquifer's productivity were found in the literature to confirm its high productivity.

Finally, the Sinai Peninsula is exposed to flash flood hazards, which will require additional costs to adopt proper measures to reduce the damages caused by such events, but it also offers an opportunity to recharge the aquifers hence increasing their potential for GW extraction.

**Nile valley and delta**

The Nile valley and delta is an important agricultural site where most of the cultivated lands are concentrated (FAO AQUASTAT 2005). GW in this highly populated area is already being used as a secondary source of water to meet domestic and irrigation water demand especially in the desert fringes (Hefny et al. 1992; Dawoud 2004; Ahmed & Ali 2011). Therefore, while the area is not suitable for establishing decentralized communities as it is already heavily populated, the availability of water that is suitable for irrigation is essential to keep lands cultivated hence keeping the jobs of a large segment of the population who are working in agriculture.

Approximately 62% of the Nile valley and delta area has access to fresh GW from the Nile basin aquifer. However, approximately 35% of the Nile delta area has access to brackish GW. The Nile Delta aquifer has the highest potential (Class I and II) for GW extraction in Egypt due to its high productivity and continuous recharge by excess irrigation water. Brackish GW extraction from this area will also reduce the water table especially in the northern parts where continuous soil salinization is reported due to the presence of brackish GW at very shallow depths (Franken 2005; Elewa & El Nahry 2009). Seawater intrusion is, however, a main limitation for further GW extraction from the
Nile Delta aquifer (Idris & Nour 1990; Sherif & Singh 1996) as it will increase GW salinity with continuous extraction. Therefore, studies to estimate the maximum amount of brackish GW that could be extracted while minimizing seawater intrusion are required, similar to the study carried out by Sherif & Singh (2002) which investigated the maximum amount of fresh GW extraction from the Nile Delta aquifer. It should be also noted that while brackish GW may exist in the fresh GW zone due salt leaching from irrigation water return, the priority should be for fresh GW extraction to reduce treatment costs.

Wadi-Al-Natrun is a depression area of around 500 km$^2$ (Idris & Nour 1990) located on the western borders of Beheira governorate and is considered as part of the Nile delta area. GW extraction, which is mainly brackish, is important in this area as it is, according to El-Kashouty & El-Sabbagh (2011), the main water source for the reclamation projects and the development of new communities in this area that started since the 1960s. However, further extraction from the Pliocene aquifer, the main aquifer in this area, is not recommended as over extraction was already reported by Hamza et al. (1984) and El-Kashouty & El-Sabbag (2011) causing a drop in piezometric heads and salt water intrusion from deeper aquifers. Brackish GW desalination is, however, required because most of the extracted GW is brackish and is not suitable for drinking. In some cases, the GW was also not suitable for irrigation as some wells, based on the study by Sharaky et al. (2007), have high levels of chloride, sodium and bicarbonate, in addition to high levels of nickel exceeding the limits recommended by the FAO guidelines (Ayers & Westcot 1994) for most of the major crops cultivated in Egypt.

**Mediterranean North West and Red Sea coastal areas**

The Mediterranean North West and Red Sea coastal areas are important touristic sites where water demand is mainly met through seawater desalination and transported Nile water (RIGW 1988). Transported Nile water, however, may not be a reliable source of water as we already discussed that Nile water is fully utilized and therefore would not be sufficient to meet additional water demand. For example, in 2012 a drop in the water level has been reported in the Al-Hammam Canal, which transports Nile water to the north west of the Mediterranean coast, due to unofficial use of the water in irrigation by the farmers, which led to severe water shortages in Marsa–Matruh city and required military interference to stop unofficial use of the water (Abd-Allah 2012; Mashaly 2012; Saleh 2012). For this reason, decentralized brackish GW extraction could be a more reliable alternative. Coastal areas are also suitable for establishing decentralized communities due to their closeness to infrastructure found in main coastal cities such as Alexandria, Marsa–Matruh, Suez and Hurghada.

GW in the coastal aquifers is a heavily underutilized resource and the aquifers have a great potential for future development. The Mediterranean North West coastal aquifer, covering an area of approximately 4,070 km$^2$, has high potential (Class II) for brackish GW extraction and therefore the area is very suitable for establishing decentralized communities. The Red Sea coastal aquifer, covering an area of approximately 15,200 km$^2$, has lower potential than the Mediterranean coastal as approximately half of its area has access to aquifers in the III to IV class range due to lower rainfall rates. However, in the area stretching between Hurghada and Ras-Ghareb cities, the Quaternary aquifer has high potential for brackish GW extraction (Class II) because it is likely to be a discharge area of the Nubian aquifer and therefore should have the priority for establishing decentralized communities along the Red Sea coast.

The main limitation for GW extraction from coastal aquifers, however, is seawater intrusion, which will require further studies to assess the maximum extractable amount of GW that will limit seawater intrusion. The Red Sea coastal aquifer is also exposed to flash flood hazards and some areas are or likely to be affected by mines and UXO.

**Solar driven decentralized brackish GW extraction and desalination systems: a key to sustainability**

It has been shown in this study that the Nile water quota is fully used and could be significantly reduced if Ethiopia carried on with constructing the Grand Renaissance Dam and used the water in irrigation. The potential increase in Nile water share depends on projects outside Egypt’s borders that are unlikely to be achieved in the near future while the measure of reusing Nile water is almost fully exploited.
Therefore, we concluded that the highly underutilized GW resources in addition to seawater desalination will be the main remaining options to increase water availability.

While GW is a limited resource compared to the essentially unlimited seawater, it is an ideal water resource for decentralized communities as it exists all over Egypt (Figures 2 and 3) allowing the use of decentralized water supply systems which are suitable for areas with a lack of infrastructure (Rommel et al. 2007) i.e. areas away from the Nile valley and delta. On the contrary, seawater is confined to coastal areas necessitating large scale centralized desalination plants to meet the water demand of all inland areas and they also have to be located in major cities where enough infrastructure exists such as power grid, water distribution network and roads (Lattemann & Höpner 2008). Furthermore, as GW extraction systems could be applied in a decentralized way, they could be easily financed instead of investing large amounts of capital in building large scale seawater desalination plants. Decentralized applications will also help creating ‘new opportunities for micro financing and local entrepreneurship thus raising the wealth in the region’ (Forstmeier et al. 2008, p. 4). Moreover, additional costs associated with pipes, pumps and energy demand will be required to convey the desalinated seawater to deep inland areas and areas located at high elevations. For example, most areas in the Western Desert are away from sea shores and are at relatively high elevation particularly south of the Al-Qattara depression where ground elevations could reach up to 1,000 m above sea level in some locations requiring high amounts of energy to convey the desalinated seawater from the nearest coastal city that can support a large scale seawater desalination plant such as Alexandria. The same applies for the Eastern Desert which is separated from the Red Sea coast by the high and rigorous Red Sea hills forming a barrier for pipeline construction. In this case, GW extraction could be more economical than seawater desalination. While brackish GW will also require desalination to be suitable for drinking, it requires less energy for desalination due to its lower salinity than seawater, especially when using a pressure driven desalination process such as Reverse Osmosis where the desalination energy is directly proportional to the water salinity, and also requires less pre-treatment (Watson et al. 2005; Younos 2005) which will further reduce the costs. According to Al-Karaghouli et al. (2010) desalinating brackish water costs three to five times less than seawater desalination for a plant with the same capacity.

Decentralized applications also offer the most sustainable use of GW resources as the small water demand would prevent GW over extraction that leads to large drops in GW levels within a short duration to the point where the cost of extracting GW could outweigh the economic return (Hefny et al. 1992). Preventing GW over extraction will also limit its salinization by either seawater intrusion or mixing with higher salinity GW from an underlying aquifer which has been reported in some areas in Egypt (Abdallah 2006; Sultan et al. 2009; Shawki 2011).

Brackish GW is favoured over fresh GW extraction because while the latter essentially needs no or little treatment to be suitable for consumption, it was found to be confined to the overpopulated Nile delta and valley area and the Western Desert. Conversely, aquifers containing brackish GW cover more than half of Egypt’s area. In addition, areas like the Eastern Desert have access to only brackish GW therefore brackish GW extraction and desalination will be a necessity to establish decentralized communities in this area. Brackish GW is regarded by many studies, such as Ahmad & Schmid (2002), Allam et al. (2005), Talaat et al. (2005) and El-Sadek (2010), as an important source to meet Egypt’s growing water demands.

GW extraction is, however, a limited resource especially when compared to Egypt’s overall water demand, estimated to be 75 billion m$^3$/year in 2009 (Ministry of Water Resources and Irrigation 2010). Therefore GW extraction is only proposed to be used to establish decentralized agricultural communities away from the Nile valley and delta that are growing high value and less water intensive crops using water efficient irrigation methods such as drip and sprinkler irrigation (FAO 2002; United Nations Country Team 2005) which can increase the income of the farmers hence their resiliency. Egypt, in general, is forced to adopt strict water saving measures including water recycling and switching to less water intensive crops, and will eventually resort to seawater desalination to meet its increasing water demand. As previously discussed, the per capita water share is already below the level associated with countries with chronic water shortages and we estimated that if all the available water quantities in Egypt, shown in Table 1, were
exploited the per capita water share will still be below 1,000 m³/capita/year even if the previously discussed projects in the Nile basin countries that could increase Egypt's Nile water share were carried out. The situation will be exacerbated if Ethiopia uses the stored water from the GRD reservoir in irrigation. In this case the aforementioned water saving measures and the building of mega scale desalination plants will need to be immediately implemented. Another limitation to extracting and desalinating brackish GW in inland areas is the disposal of the produced brine that has a high salt concentration and filled with different feed water pre-treatment chemicals, which raises environmental concerns in addition to the energy and extra costs required for its disposal (Eltawil et al. 2009).

Finally, as Egypt has limited supplies of fossil fuels and the prices of fuel commodities are increasing, solar driven GW extraction and desalination will guarantee a long-term supply of energy and minimal susceptibility to global market prices compared to the volatile fossil fuel prices (International Renewable Energy Agency 2012). Many studies such as Abdelrassoul (1998), Ahmad & Schmid (2002), García-Rodríguez et al. (2002), Fiorenza et al. (2003), García et al. (2003) and Kalogirou (2005) regarded solar energy as the most appropriate and promising renewable energy source to drive desalination plants in remote arid areas, which also applies for GW extraction. Solar energy is a locally and a highly available energy resource, a main requirement for establishing resilient and sustainable communities (Rheinländer 2007). In Egypt the annual average global irradiation mostly falls in the 6 to 6.5 kWh/m²/day range, which is one of the highest in the world based on NASA solar world map (NREL 2013). Solar energy also has a low environmental impact in terms of greenhouse gas emissions in addition to its simplicity of operation and low maintenance requirements (Richards & Schaefer 2003), which are both necessary for a successful implementation and operation in rural areas. Solar energy, particularly photovoltaic modules, is also described by Retnanestri (2007, p. 10) as a ‘democratic technology’ due to its modularity and that it can be installed and operated by the locals once they have a sufficient training hence the technology is available for any community, or stakeholder in general, desiring to supply its own energy needs (International Renewable Energy Agency 2012).

CONCLUSION

Egypt’s share from Nile water, the main source of fresh water in Egypt, is fully utilized and the available quantity could potentially decrease by approximately 19% if Ethiopia carries out its proposed land reclamation scheme while measures like Nile water reuse are almost fully exploited. For this reason, seawater desalination and GW extraction will be the remaining options to increase Egypt’s water supply. Brackish GW extraction and desalination could potentially be a more economical solution than seawater desalination as it suits decentralized applications and therefore could be used to establish decentralized agricultural communities to increase the resiliency of the population and reduce poverty rates. Reviewing GW in the main seven hydro-geological systems in Egypt showed that the country has a great potential for brackish GW exploitation where more than half of its area has access to brackish water aquifers. The study also showed that 47% of brackish water aquifers have moderate to high potential for sustainable extraction. Five main areas were identified to have priority for establishing decentralized agricultural communities based on brackish GW extraction and desalination: areas along the Nile River in the Western Desert and the Eastern Desert having access to the Nubian aquifer and the shallow Quaternary aquifer; the central parts of the Sinai Peninsula tapping the Quaternary and the Nubian aquifer; the coastal area along both shores of the Suez Gulf; and the Mediterranean North West coastal area. Brackish GW extraction and/or desalination could be also required in: the northern parts of the Western Desert to supply water for oil and gas companies; in the Siwa depression area and the Nile delta to lower the water table and prevent soil salinization; and in the north east coastal area of the Sinai Peninsula as brackish or polluted GW was reported to be used for drinking causing diseases.

REFERENCES


Abdallah, G. 2006 Management of groundwater aquifers along the mediterranean sea in Sinai Peninsula. The 2nd International Conference On Water Resources And Arid Environment King Saud University Riyadh.


El-Behary, H. 2012 Continuous blackouts hit Egypt metal industries hard.


Hassan, T. H., Attia, F. A. & El-Attfy, H. A. 2004 Groundwater potentiality map of the Nile basin countries – a step towards integrated water management. *International Conference And
Exhibition On Groundwater In Ethiopia: Providing Water For Millions, Addis Ababa.

Hefny, K. & Shata, A. 2004 Groundwater In Egypt. Ministry of Water Supplies and Irrigation, Cairo.


Hoelzgen, J. 2008 Landmines in the desert sand: Nazi landmines block Egypt’s access to oil and gas. http://www.spiegel.de/international/world/0,1518,540756,00.html


International Campaign To Ban Landmines. 2010 IDA Desalination Plants Inventory. Global Water Intelligence and Water Desalination Report.

International Desalination Association 2013 IDA Desalination Plants Inventory. Global Water Intelligence and Water Desalination Report.


Leila, R. 2012 Power to the people?


Loneragan, S. & Wolf, A. T. 2001 Moving water to move people, the toshka project in Egypt a water forum contribution. Water International 26, 589–596.


Research Institute for Groundwater 1988 Hydrogeological map of Egypt. RIGW, Kalibiouia, Egypt.


Sabry, B. 2012 A guide to Egypt’s challenges: fuel & electricity shortages.


Viney, S. 2012 Rural irrigation canals are afflicted by water shortages and contaminated water. Egypt Independent, 13 August.


First received 18 September 2013; accepted in revised form 18 December 2013. Available online 21 February 2014.