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PAPER

Review: Toward sustainable management of groundwater in the deserts of Egypt

Doaa E. El-Agha[1] · Francois Molle[2] · Mohamed I. Metwally[3] · Sobhy R. Emara[3] · Ahmed Shalby[3] · Asaad M. Armanuos[3] · Abdelazim Negm[4] · Tamer A. Gado[3]

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Abstract
To achieve its ambitious plans to reclaim its deserts through mega projects, Egypt is heavily relying on fossil or little-recharged groundwater. This article revisits the results and methodologies of the studies conducted over the last two decades on groundwater management and uses in the Western Desert. Most previous studies aimed at simulating different groundwater abstraction scenarios by modeling local areas in aquifer systems, but with poor definitions of boundary conditions and limited historical data. Studies were constrained by the unavailability of data, access difficulties, and high collection costs in desert lands. Thus, to propose reliable sustainable groundwater resources development plans and recommendations for future protection strategies, an open-access monitoring network representing regional aquifers is needed. More investigations based on extensive field visits are essential to monitor environmental, economic, and social conditions, identify constraints, and learn lessons for reclaiming desert lands. Moreover, this review highlighted the need to frame a rational strategy for the long-term sustainable exploitation of non-renewable groundwater in the aquifer systems of Egypt and develop an appropriate exit strategy for desert communities in case of serious water resource depletion.

Keywords Egypt · Groundwater management · Numerical modelling · Desert lands · Sustainability

Introduction

The United Nations' Sustainable Development Goals (SDGs) are encapsulated in the 2030 Agenda and its 17 goals, which aim to end poverty, protect the environment, and improve the lives of all. More than 53 targets are interlinked with groundwater, a resource that is therefore key to achieving the 2030 Agenda. Many countries depend on groundwater for their development, and more than half of the world's food is irrigated using groundwater (Famiglietti 2014; UNESCO 2022). However, worldwide, groundwater is poorly monitored and managed in many countries, especially in developing countries in arid and semiarid regions that heavily rely on groundwater as a resource (Famiglietti 2014; Molle and Closas 2017). Many of the world's major aquifers in dry areas are experiencing rapid depletion (Richey et al. 2015).

Since the 1950s, the government of Egypt has carried out successive land reclamation projects, with a total agricultural land area reaching 9.42 million feddan (1 feddan = 0.42 ha) in 2020 (FOASTAT 2022). Egypt's current surface water resources are limited and fully used, and the scope for overall water savings as a means of cultivating more land is small (Molle et al. 2018). Surface water shortages and management problems have fueled the expansion of groundwater use in the Nile delta in the past 30 years (El-Agha et al. 2017). Furthermore, loosely regulated expansion by investors in the western Nile Delta (El Quosy 2019; Youssef et al. 2021), along with recent land expansion plans by the government, have increased pressure on groundwater resources. Development projects have been planned, including several irrigation megaprojects, to increase the cultivated area by 4 million feddan, interspersed across Egypt's desert lands (SIS 2016). The first phase involved 1.5 million feddan and was initiated in 2016 (MWRI 2017). This plan mainly relies

✉ Doaa E. El-Agha
d.elagha@eng.suezuni.edu.eg

1 Faculty of Engineering, Suez University, Suez, Egypt

2 Institut de Recherche Pour Le Développement, Marseille, France

3 Faculty of Engineering, Tanta University, Tanta, Egypt

4 Faculty of Engineering, Zagazig University, Zagazig, Egypt

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on tapping fossil groundwater in desert lands for irrigation, which necessarily leads to the depletion of the aquifers. By bringing the marginal cost of pumping to zero, the use of solar energy is also expected to encourage groundwater over-abstraction in the absence of appropriate policies, regulations, and incentives. Recently, in 2021, the massive "New Delta" project was launched with the aim of reclaiming an additional 2.2 million feddan in the Western Desert, based on groundwater, Nile water, and treated wastewater (SIS 2022). However, the harsh climatic conditions in desert lands hinder development and limit their attractiveness for settlers or investors (Sims 2015).

Studies aimed at ensuring the sustainable use of groundwater resources are therefore of great importance to both the government and investors in the agricultural sector. Most past studies involved the use of groundwater modeling to assess the impact of exploitation, test proposed development plans, and predict future changes in groundwater availability and potential deterioration caused by pumping. This article reviews the methodologies and results of the studies conducted over the past decades on groundwater utilization and management in the Western Desert of Egypt. It identifies the rates of exploitation and depletion, and the limitations and knowledge gaps, and attempts to explain the extreme variability in the results of these scientific studies. It shows that the current knowledge on groundwater resources and use in Egypt's deserts is still largely inadequate to properly plan agricultural expansion. The article suggests some strategies and options for future research and applied policies.

Overview of groundwater resources in the Western Desert of Egypt

The groundwater resources of Egypt include six main aquifer systems (RIGW 1988; Fig. 1). These groundwater sources are nonrenewable or semirenewable, with the exception of the Nile Delta and Valley aquifer, which is hydraulically connected to the Nile River and is also recharged by irrigation. The hydrological system in the Western Desert consists of three main aquifer systems – the Nubian Sandstone Aquifer System (NSAS), the Fractured and Karstified Carbonate

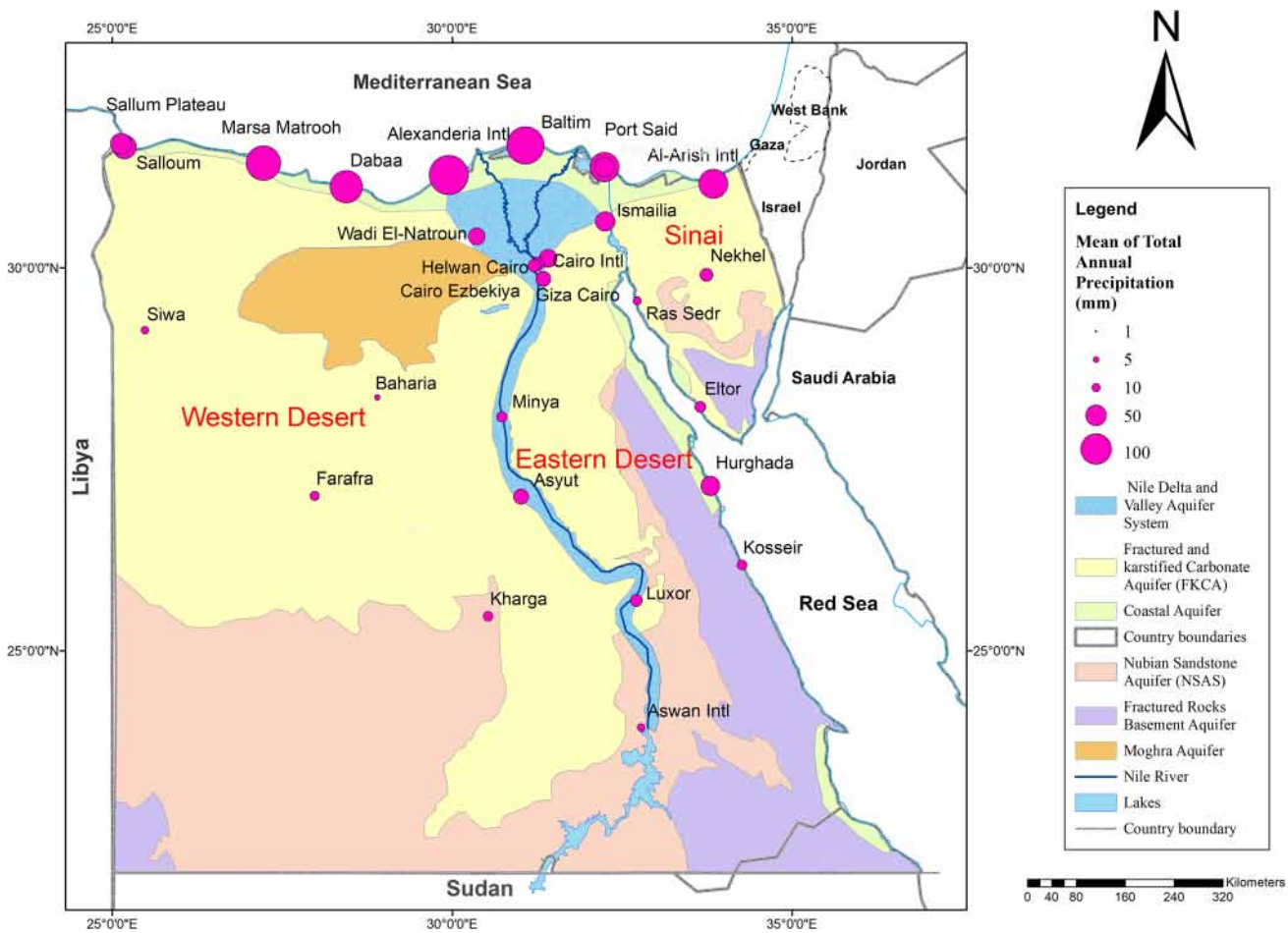

Fig. 1 Aquifer systems (RIGW 1988) and mean annual precipitation (Gado and El-Agha 2020) in Egypt

Aquifer (FKCA) system, and the El-Moghra Aquifer system – which are the focus of this article.

Nubian Sandstone Aquifer System (NSAS)

The NSAS is the second largest source of fresh groundwater resources in Egypt. It is a transboundary aquifer shared by Egypt, Libya, Sudan, and Chad that covers an area of about 2.35 million km^2. It is considered as a nonrenewable groundwater system with a high reserve estimated at 150,000 billion m^3 (BCM) (Thorweihe and Heinl 1996), including 40,000 BCM in Egypt (El-Rawy et al. 2020). The aquifer system contains fossil water that was stored during the past humid Pleistocene age (0.2 to 1.0 million years) (Sturchio et al. 2004). The NSAS is flowing from the South to the Northern plateau, but also occurs in the south of the Sinai Peninsula and the Eastern Desert (El-Rawy et al. 2020). In the Western Desert, the NSAS aquifer is unconfined in its southwestern part but is in confined to semiconfined conditions to the north, under a thick low-permeability layer. The hydrogeology of this aquifer system has been investigated since 1927 in the Western Desert development areas of El-Kharga, El-Dakhla, El-Farafra, El-Bahariya, Siwa, East-Oweinat, South El-Kharga and Toshka basin through deep oil exploration wells and 500 wells drilled at depths ranging from 500 to 1,200 m. The thickness of NSAS increases spatially from 200–700 m in East Oweinat area, 300–900 m in EI-Kharga, 1,500 m in El-Dakhla, 1,800 m in El-Bahariya, 2,200 m in El-Farafra Oases, to 3,500 m west of El-Farafra (USAID 1998). Also, water quality in the NSAS varies across the Western Desert laterally and vertically, e.g., with a high content of iron and manganese reported in El-Farafra and El-Bahariya oases. The salinity increases with depth in Siwa Oasis: at shallow depths the salinity is in the 200–400 ppm bracket, but it is underlain by hyper-saline water with salinity reaching 100,000 ppm (USAID 1998). In contrast, the groundwater salinity in El-Kharga and El-Dakhla oases decreases from 1,000 ppm at shallow depths to 200 ppm at deep depths (Korany 1995; USAID 1998).

Fractured and Karstified Carbonate Aquifer (FKCA)

The FKCA system occupies more than 50% of Egypt's land and is found in the Western Desert, Eastern Desert, and Sinai Peninsula (Fig. 1). FKCA consists of limestone, dolomites, marls, chalk and shales (USAID 1998). The aquifer system feeds more than 200 springs in the Western Desert, with a total flow of 200,000 m^3/day (El-Rawy et al. 2020). The direction of the regional flow is from southeast to northwest and from highlands toward lowlands. The NSAS is bordering the FKCA from the southern parts along El-Kharga and El-Dakhla Oases, and extends beneath the FKCA, separated by low-permeability shale limestone, which provides recharge by upward leakage through existing deep faults. Research studies therefore refer to it as the Post-Nubian Sandstone Aquifer System (P-NSAS; El-Ramly 1967; USAID 1998; EL-Rawy et al. 2020).

The thickness of the FKCA ranges from 150–200 m in El-Farafra Oasis to 500–10,000 m in the Siwa Oasis and the Qattara depression area. The salinity of groundwater varies from freshwater (<1,000 ppm) in El-Farafra oasis to brackish (2,000–5,000 ppm) in the Southern part of the northern plateau, and can even exceed 10,000 ppm towards the Qattara depression (USAID 1998; El-Rawy et al. 2020). Until 1998, the estimated abstraction rate from the FKCA was about 272 million cubic meters (MCM/year) from 1,516 shallow wells and springs in El-Farfara and Siwa oases (USAID 1998).

El-Moghra Aquifer system

El-Moghra Aquifer system, covering a total area of about 50,000 km^2 (Dawoud et al. 2005), extends from the western borders of the Nile Delta at Wadi El-Natroun and Wadi Farigh to the Qattara Depression westward, and to the Fayoum Depression southward (Fig. 1). The aquifer system consists of sand and gravel of the lower Miocene, with a thickness ranging from 50 to 250 m in the eastern part at Wadi El-Natroun and increasing in the northwest direction to reach a maximum value of about 1,000 m in the Qattara Depression (Abdel Mogith et al. 2013; Mashaal et al. 2020). The NSAS underlies the El-Moghra aquifer system and recharges it by upward artesian leakage from deeper layers (Rizk and Davis 1991; Ezzat 1982). Groundwater flows to the west through Wadi El Farigh to Qattara Depression (134 m below sea level), which acts as a discharge area (Abdel Mogith et al. 2013). El-Moghra aquifer is unconfined to the east but confined to the west, due to the existence of an overlaying layer ("Marmarica limestone"). It is considered a semirenewable aquifer, as it is recharged from: (1) the Nile aquifer system at a rate of 50–100 Mm^3/year (RIGW 1998), (2) NSAS at a rate of 75–90 Mm^3/year (Ezzat 1982; Rizk and Davis 1991), (3) seepage from the overlaying Miocene limestone aquifer (the rate is unknown), and (4) (negligible) contribution from rainfall. The discharge from the aquifer takes place through groundwater abstraction for agriculture areas to the west of the Nile Delta and around El-Moghra Oasis (200 Mm^3/year; El-Tahlawi et al. 2008), evaporation from the Qattara Depression—90 MCM/year (Ezzat 1982)—and by lateral seepage into the carbonate rocks of the western part of Qattara Depression (at an unknown rate). Water salinity varies from 289 ppm near Wadi El-Natroun, to 10,000 ppm at El-Moghra oasis, and to 31,000 ppm near the Qattara Depression (Geirnaert and Laeven 1992; Abdel Mogith et al. 2013; El-Tahlawi et al. 2008).

Development plans to reclaim Egypt's deserts

The Nile Valley and the Nile Delta make up the most fertile agricultural lands of Egypt (FAO 1997). Egypt's deserts are commonly divided in three subareas—the Western Desert, the Eastern Desert, and the Sinai Peninsula (Fig. 1). The Western Desert includes the Coastal Plain, the Northern Plateau, the Qattara Depression, Wadi El-Natroun, and the Bahariya Oasis, and to the south, the oases of Siwa, Farafra, Kharga, Dakhla, and East Oweinat (Hefny and Sahta 2004).

The idea of reclaiming desert land has been at the forefront of the successive government agendas since 1950, with the main goals of achieving food self-sufficiency and resettling the population from the narrow valley and the delta to the desert lands, which represent 94% of Egypt's land. In 1997, the government initiated a 5-year plan to reclaim 3.4 million feddan and attract large investors in agricultural projects. Out of this area, 2.9 million feddan (1.2 Mha) were located in the Western Desert (East Oweinat, Western Oases, and Drab El-Arbaein) based on deep groundwater, but the project faced many challenges and failed to attract investors as planned (USAID 1998). Several social and technical difficulties emerged such as waterlogging and soil salinization, high contents of undesirable minerals, soil infertility, costly electricity supplies, lack of qualified technicians, and above all social difficulties due to lack of services (Hanna and Osman 1995; DDC 1997). In 2015, the area cultivated in the oases did not exceed 120,000 feddan (50,400 ha; Sims 2015; Molle 2018).

In 2014, the old reclamation projects in the New Valley (Oases and Toshka) were revived, with the announcement of a new megaproject for the reclamation of 4 million feddan in three phases. The first phase started in 2016 and included the reclamation of 1.5 million feddan in eight governorates—El-Minia, Qena, Aswan, Elwadi Elgideed, Matrouh, South Sinai, Ismailia, and Giza (MWRI 2017). As shown in Fig. 2a, most of these lands are located in the Western Desert, with 90% of them depending on the non-renewable groundwater of the Nubian Sandstone Aquifer and El Moghra Aquifer. The goal is, again, to establish new

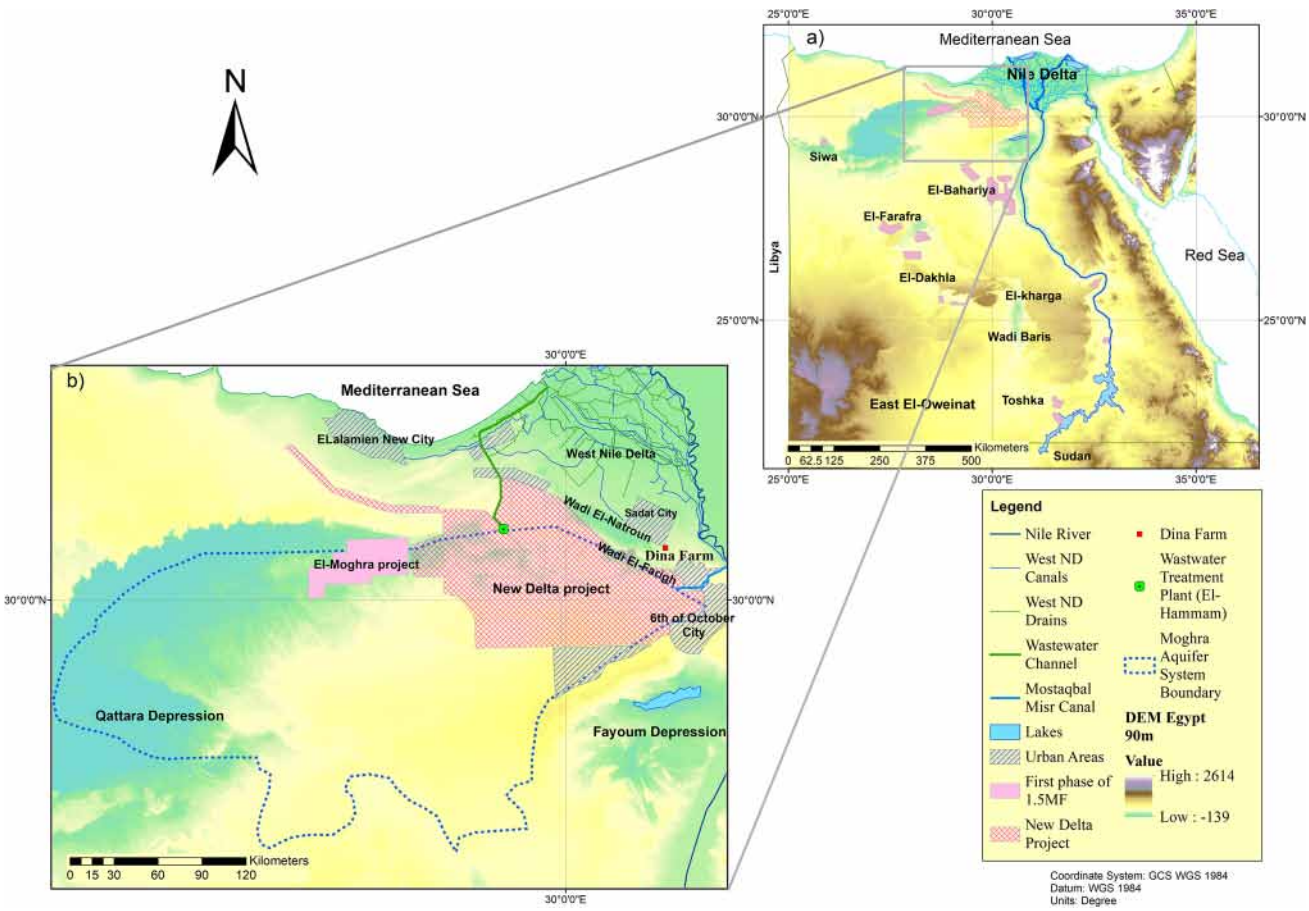

Fig. 2 **a** Location map of the 1.5 million feddan (1.5MF) project, **b** Location of the New Delta project and El-Moghra Aquifer. DEM digital elevation model, ND Nile Delta

integrated agro-industrial communities in the desert lands. The project drilled 949 wells in the first phase, out of a total of 5,111 wells planned, at a cost of 1.1 billion EGP (4 million $US). These wells tap deep groundwater at depths ranging from 125 to 1,000 m with pumping rates between 1,200 and 2,500 m^3/day per well (MWRI 2021).

In addition to the factors mentioned previously, reclamation efforts in desert lands also face challenges such as water quality deterioration, increasing pumping costs, energy availability, corrosion problems in wells (due to iron and manganese reported in Farafra and Bahariya oases), technical problems with drip irrigation, and climate hazards—for instance, in 2020, heavy rains and strong winds (Dragon Storm) caused severe damage to some areas in El-Moghra, which forced the government to pay compensation to affected farmers (Negm et al. 2021).

Review of groundwater modelling studies conducted in the Western Desert of Egypt

Studies of groundwater in the Western Desert started in 1956, to investigate the potential of the NSAS in the oases (El-Dakhla -El-Kharga, El-Farafra, El-Bahariya) by drilling 500 exploratory and production wells at various depths, conducting electrical logs and pumping tests. The regional piezometric maps from 1960 show water levels and estimation of annual extraction. In addition, regional studies have been carried out to define the aquifer geometry, hydraulic characteristics, water level evolution and historical abstraction. Groundwater modelling developed from 1968 onward, covering regional and local areas in the Western Desert, in order to analyze and assess the behavior of the aquifer under current exploitation and plans of further development.

A regional model by Borelli and Karanjac (1968) tested the exploitation of 985 MCM/year from El-Dakhla and El-Kharga Oases and the predicted drawdown ranged from 65 to 110 m after 50 years (1967–2017). FAO (1976) developed a mathematical model for extracting 696 MCM/year to irrigate 24,360 ha in El-Dakhla and El-Kharga Oases and predicted an average drawdown ranging from 13 to 85 m after 50 years. These coarse models did not take into consideration the interaction between aquifer systems vertically and laterally. In 1983, various groundwater development scenarios for the four oases—El-Dakhla, El-Kharga, El-Farafra and El-Bahariya—were tested by Euroconsult/Pacer Consultant (1983) using a mathematical simulation model to predict aquifer response after 100 years (1985–2085) of exploitation. They estimated the economical depth of pumping from the aquifer and suggested maximum pumping depths for each oasis (e.g. for El-Farafra 122 m, El-Bahariya 96 m, El-Kharga 38 m and El-Dakhla 63 m).

Thanks to the rapid development of computational technologies and software, numerical models have become more accessible and more effective in solving groundwater flow equations. Groundwater flow in the entire NSAS has been investigated by several researchers (e.g., Brinkmann and Heinl 1986; Sonntag 1986; Ebraheem et al. 2002; Heinl and Thorweihe 1993), covering a large portion of Egypt. Recent government plans have led to a renewed interest in modeling and defining the sustainable exploitation rate of the NSAS. The following summarizes and compares the results derived from numerical models used to predict the response of the aquifer systems in the Western Desert oases and El-Moghra region to various groundwater development scenarios.

Nubian Sandstone Aquifer System modelling studies

Before 1938, the exploitation of groundwater in El-Kharga oasis was limited to natural springs and shallow wells at depths between 50 and 70 m. Between 1938 and 1952, six deep wells (300–500 m) were drilled to test the aquifer potential for implementing the 'New Valley' large-scale land reclamation project in 1960. In 1998, groundwater extraction was estimated at 118 MCM/year to irrigate 7,140 ha, while between 1960 and 1998 the natural discharge of artesian wells decreased from 3,598 to 1,400 m^3/day and groundwater levels declined by 0.13 to 2.2 m/year, prompting further groundwater development in El-Kharga oasis to be restricted (Hefny and Sahta 1996; USAID 1998). Twenty years later Mekkawi et al. (2017) observed a groundwater level drawdown of 60–80 m (bgl) in the northern part and 40–60 m (bgl) in the southern part of El-Kharga oasis between 1967 and 2007. In 2013 Mahmod et al. (2013) combined a numerical model, 2D-FEM, with genetic algorithms (GAs) and found that groundwater levels could further fall by 47 m by 2060 in the northeastern part of the study area, while the hydraulic head difference between the northern and southern parts would reach 140 m. According to El-Rawy and Smedt (2020), the irrigated area in El-Kharga oasis reached 11,400 ha, sourcing groundwater from 1,100 shallow wells owned by farmers, abstracting about 8.3 MCM/year, in addition to 300 deep wells owned by the government, abstracting 198 MCM/year. This chronology shows that state-led development proceeded despite restrictions and falling water levels.

In the El-Dakhla depression, the observed drawdown in piezometric pressure was, similarly, about 1.2–2 m/year between 1960 and 1998 (USAID 1998). During the same period, the groundwater extraction rate increased from 118 MCM/year (632 shallow wells and 15 deep wells) to 291 MCM/year (505 shallow wells and 305 deep wells), and the irrigated area increased from 4,200 to 15,750 ha, resulting in a decrease in the discharge of artesian wells from 6,923 to 1,891 m^3/day (USAID 1998). In 2011 Gad et al. (2011)

found an area of 23,226 ha irrigated by 238 shallow and deep wells extracting about 187 MCM/year (0.512 MCM/day, a value estimated based on the irrigated area). Gad et al. (2011) used MODFLOW in combination with a multiobjective genetic algorithm to test the effect of the actual extraction rate (0.512 MCM/day from 84 shallow and 154 deep wells) and found that the drawdown in the central area could reach 26 m after 40 years, or 30–60 m if abstraction was increased by 20%. Sefelnasr et al. (2014) considered an actual pumping rate of 1.2 MCM/day, much higher than in Gad et al.'s study, and estimated a depth to water of 75 m after 90 years. A rate of 1.46 MCM/day was found to be optimal in keeping the depth to water under 100 m, while higher rates (1.7 MCM/day) resulted in severe depression cones. In the 1980s, the 'economic groundwater extraction' was calculated at 374 MCM/year, while USAID (1998) predicted that after 100 years of exploitation, the depth to groundwater in the oasis would be 62 m (bgl). Kimura et al. (2020) recently reported an abstraction rate of 430 MCM/year for a cultivated area of 46,000 ha, pointing to continued growth in water use and that depth to water would reach the uneconomical threshold of 100 m within 90 years. However, the study of agricultural dynamics by Kato et al. (2014) shows that a lot of other dynamic parameters need to be considered to fully appreciate the situation: change in cropping patterns, crop rotations and fallowing, spatial shifts, types of wells, decreasing well productivity and artesianism, etc.

In El-Farafra, 78 wells were drilled in 1985, increasing to 97 in 1998 to yield an artesian flow of 160 MCM/year (0.44 MCM/day) mostly (96%) used to irrigate 5,880 ha. The observed drawdown in piezometric levels was 0.14–0.42 m/year for the period 1965–1983 (USAID 1998). El Sabri and El Sheikh (2009) reported that during the period 1962–2008, the number of naturally flowing springs decreased from 67 to 11 springs, while the number of deep wells increased from 18 to 140 wells, irrigating an area of 20,580 ha, therefore almost four times larger than a decade earlier. In spite of this, they used an actual extraction rate (0.49 Mm^3/day) close to that of 1998, considering 140 wells, and predicted a drawdown ranging from 5 to 9 m after 20 years. Saafan et al. (2011) used MODFLOW combined with a multiobjective genetic algorithm and recommended two optimal scenarios: (1) extraction of 0.19 MCM/day for 15 years at a cost of 1,79 MLE ($280,000) which would result in a drawdown of 6 m, and (2) extraction of 0.179 MCM/day for 50 years at a cost 3.02 of MLE ($500,000), which would result in a drawdown of 8 m. Similar scenarios were recommended by Moharram et al. (2012), with 0.182 and 0.193 MCM/day, and which would cause a drawdown of 6.40 and 8.57 m, respectively, by 2050. Likewise, El-Sheikh (2015) tested management plans with a 20-year horizon, considering both present (0.73 MCM/day for 29,400 ha) and future pumping schemes and recommended reducing pumping rates by 20% by adopting drip irrigation, while reclaiming an additional 4,620 ha, with a total pumping rate of about 0.878 MCM/day, which would cause a spatially varying drawdown between 12 and 20 m by the end of 2033, compared to 18–30 m for a do-nothing scenario. In a recent study, El-Mansy et al. (2020) applied the Ministry of Water Resources and Irrigation (MWRI)'s new sustainability targets in terms of duration (lifting depth remaining economic for 100 years) and depth to water (limited to 40 m) to a proposed reclaimed area of 4,200 ha, and estimated that the most beneficial extraction rate would be 0.120 MCM/day. What stands out in these studies is the very high variability in the abstraction (m^3)/area (ha) ratio, pointing to a lack of accurate monitoring.

In El Bahariya Oasis, natural springs and shallow wells were producing ~33 MCM/year in 1960. During the period of 1963–1997, the observed decline in the piezometric head was 1.2 m/year and the number of deep wells increased from 7 to 59, the extracted rate reaching ~65.6 MCM/year, 89% of which was allocated to irrigate an area of 5,040 ha (USAID 1998). RIGW (2010) indicated the extraction of 100 MCM/year from the groundwater in Bahariya to irrigate an area of 6,590 ha, a rate found to be 116 MCM/year in 2012 (with 883 wells; Sharaky et al. 2021). Using the FEFLOW numerical model, Himida et al. (2011) considered an actual abstraction of 34.8 MCM/year for 5,000 ha. They recommended an economic abstraction rate of 0.837 MCM/day from the NSAS to cultivate an area of 21,980 ha with a permissible drawdown of 1 m/year. El Hossary (2013a) simulated groundwater flow and expected a drawdown of up to 26 m after 25 years at an extraction rate of 0.651 MCM/day. More recently, Sharaky et al. (2021) estimated the current extraction rate at 108 MCM/year and an expected drawdown from 4 to 32 m in 50 years, concluding that expansion is warranted.

Siwa Oasis is located in the south-west Qattara Depression area and has groundwater levels at 10–18 m below mean sea level (bmsl). Before 1980, the water discharging from 200 natural springs with an estimated rate of 70 MCM/year would irrigate 840 ha. During the period of 1981–1992, farmers constructed 1,000 shallow wells (20–40 m deep) yielding 105 MCM/year in addition to 200 wells (70–80 m deep) yielding 70 MCM/year. In 1996, five deep wells constructed by the army added 20 MCM/year (USAID 1998). The cultivated area increased from 4,200 to 8,400 ha during the period 1998–2013 with an increase of abstraction rate from 196 MCM/year to 225 MCM/year, respectively (El-Hossary 2013b; Abo-Ragab 2010; EuropeAid 2013). Soil salinization, drainage problems and waterlogging have been experienced since 1998, especially in low lands around lakes (USAID 1998; El-Deen 2021).

East-Oweinat is one of the development areas initiated in 1988 to reclaim 79,800 ha (190,000 feddan) by the end of the year 2022 in the southwest of the Western Desert. A

finite element model was developed by DRTPC (1984) to investigate the long-term aquifer response to groundwater development exploitation, and a proposed extraction plan of 474 MCM/year for 100 years was considered with a predicted drawdown ranging from 35 to 100 m. However, Nour (1996) indicated that the extraction rate of 1.4 BCM/year is sustainable for the coming 100 years with an expected drawdown of 1 m/year. Ebraheem et al. (2002) used MODFLOW and the historical data of 850 water wells drilled from 1960 to 2000 to model the NSAS in the Western Desert (630,000 km^2) and derived a finer grain model (2,760 km^2) to investigate different extraction rates in East-Oweinat (Ebraheem et al. 2003). They concluded that extracting 1.2 BCM/year would cause a drawdown greater than 140 m after 100 years and would lead to a cone of depression that could affect other reclaimed areas in El-Kharga and Dakhla Oases (Ebraheem et al. 2003). Also, El-Alfy (2014) developed a MODFLOW model to test an extraction rate of 1.4 BCM/year and found it would cause a drawdown of 30 m at the end of a simulation period of 30 years (1 m/year). It is worth mentioning that the area under cultivation currently (2022) in East Oweinat is 378,563 ha, making these studies quite contradictory with regard to their conclusions.

A summary of methodologies used in modelling studies for the NSAS in the Western Desert during the last 20 years is given in Table 1. This compares the numerical code used, areas modeled, assumed boundary conditions, input hydraulic parameters, data used for calibration, and the expected drawdown due to the management scenarios considered.

El-Moghra Aquifer system modelling studies

El-Moghra aquifer system is semirenewable since it receives an amount of recharge from the Nile Delta aquifer and the Nubian Sandstone, as mentioned earlier. Groundwater abstraction has increased rapidly due to the uncontrolled growth in reclaimed areas in the last three decades on the eastern part of El-Moghra aquifer. Initially the use of groundwater was limited to a small number of farms located at the end of the irrigation system, but after the 1992 expansion soared without any control or regulations. The manifestations of aquifer depletion were noticed after a few years in different locations such as Dina Farm (Gawad and Bekhit 2014; El Quosy 2019). Groundwater salinity increased to 1,500 ppm, due to return flow from the drip irrigation system, the water table dropped by more than 20 m, and land deteriorated (Negm et al. 2021; MWRI 2005). Impervious soil layers that limit percolation created drainage and water logging problems (El Abd and El Osta 2014; Amer 2021).

Until 1998, the abstraction rate from El-Moghra aquifer was estimated at 52.3 MCM/year, and the water was used to irrigate an area of 5,334 ha in Wadi El-Farigh, where an assessment study pointed to the feasibility of a long-term extraction of 120 MCM to irrigate 14,700 ha (35,000 feddan; USAID 1998). Youssef et al. (2021) indicated that an area of 336,000 ha (800,000 feddan) is now supplied with water from the eastern part of El-Moghra Aquifer in Wadi El Farigh (Fig. 2). The Miocene aquifer water level decreased at a rate from 1.3 to 1.7 m/year during the period from 2003 to 2015 and groundwater salinity increased from 300 ppm in 2003 to more than 2,000 ppm in 2012, due to intensive exploitation (Youssef et al. 2021).

In the last 10 years, studies have been conducted on El-Moghra aquifer to optimize the use and management of groundwater and to reduce adverse consequences (Table 2). In Wadi El Farigh, two studies have been conducted using a MODFLOW model to assess the expected drawdown for a simulation period from 2006 to 2050. Youssef et al. (2012) predicted a decline of 30 m and Khalifa (2014) of 17.2 m, despite almost doubling the simulated pumping discharge from 0.303 to 0.569 MCM/day. Youssef et al. (2012) recommended reducing pumping rates and constructing a new canal for diverting water from the River Nile to maintain the depth-to-groundwater at 16 m.

In the Qattara Depression, in the north-west of El-Moghra aquifer, since 2016, the government has been reclaiming land in a new project of about 71,400 ha (170,000 feddan), as part of the "1.5 million feddan project" (Fig. 2b). El Sabri et al. (2016) used MODFLOW to predict a decline in the water table of 28 m after 50 years, assuming an extraction of 0.3 MCM/day. They recommended irrigating only 42,000 ha (100,000 feddans), which would limit groundwater decline to 0.53 m/year over a time span of 100 years. Gomaa et al. (2021) investigated the flow and salinity distribution of groundwater in an area where 445 wells were drilled in 2018 to reclaim 84,000 ha. Using SEAWAT they concluded that irrigating this full area (scenario 3) with 0.7 MCM/day would cause a drawdown of 58–81 m and a salinity increase between 7 and 17%, according to the well location, after a simulation period of 100 years. Likewise, using MODFLOW, Sayed et al. (2020) tested several scenarios over a period of 100 years and recommended cultivating an area of 36,000 ha, with a total abstraction of 2.88 MCM/day from 1,000 wells, which would cause a drawdown of 92 m (less than 1 m/year). Ragab et al. (2019) used the Visual MODFLOW software to test different pumping scenarios over a 50-year period. They predicted a drawdown of 369 m for an abstraction of 1.86 Mm^3/year (full development of 170,000 feddan) and recommended reducing planned pumping rates by 70% to extend the lifetime of the aquifer. It is believed that the aquifer is "probably recharged through upward leakage under artesian conditions" (Sayed et al. 2020), which serves to underline the high uncertainty inherent in these quantitative projections.

Table 1 Summary of recent studies on groundwater management modeling conducted on NSAS during the past 20 years

Study	Location	Area modelled (km^2)	Modelling code	Boundary conditions	Input parameters				Water management simulation		
					Storativity	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Data used for calibration (No. of wells)	Simulated pumping discharge rate (m^3/day)	Simulated period start–end (year)	Predicted drawdown (m)
Ebraheem et al. (2003)	East Oweinat	2,760	MODFLOW	- No flow at the E, SE, and N - Constant flux at SW - Constant head at Lake Naser	10^{-3}	-	10–20	Observed heads (1960–2000)	3,333,000	2000–2100	140
El-Alfy (2014)	East Oweinat	6,500	MODFLOW	- Specific head at the S and N - No flow at the E and W - Point of well discharge	10^{-3}	-	10–20	Water levels in 2003–2006–2011 (31 wells)	3,800,000	2011–2041	30
Mahmod et al. (2013)	El-Kharga Oasis	186,998	Grey Model (GM) and 2D-FEM	- Fixed boundary head with the flow direction from the southwest to the northeast	3.28×10^{-3} -3.28×10^{-2}	50–500	-	Water levels (1979–2005) (4 wells)	-	2010–2060	47
Gad (2011)	El-Dakhla	4,000	MODFLOW and GA	- Open flow for the SE and NW - General head in the SW (207 m) and NE (140 m)	-	-	-	Water levels measured in 2008 (12 wells)	511,783	2008–2050	26
Sefelnasr et al. (2014)	El-Dakhla	Local model from regional model 2.35×10^6	FEFLOW	- Fixed head (175 amsl) at the E (Lake Nsser water level) - No flow at N, W,S - Wells discharges	_	7.5×10^{-2}	4.8×10^{-5}	Water levels (1960–2005) (56 wells)	1,200,000	2005–2100	75
El Sabri and El Sheikh (2009)	El-Farafra	3,600	MODFLOW	For first layer Post Nubian Aquifer - No flow for the E and W - General head at the S (120 m) and N (50 m) For second layer Nubian Aquifer - General head at the S (130 m) and N (60 m)	-	520 1,250 720	-	Water levels measured in April 2008	490,000	2009–2029	5–9
Moharram et al. (2012)	El-Farafra	737.3	MODFLOW and GA	- Constant head NW (95 m), and SE (136 m) - No flow at NE and SW	-	-	-	Contour map of water levels from El Sabri and El Sheikh (2009)	172,484	2010–2060	4.60–8.30

Table 1 (continued)

Study	Location	Area modelled (km^2)	Modelling code	Boundary conditions	Input parameters				Water management simulation		
					Storativity	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Data used for calibration (No. of wells)	Simulated pumping discharge rate (m^3/day)	Simulated period start–end (year)	Predicted drawdown (m)
El-Sheikh (2015)	El-Farafra	4,550	MODFLOW	- No-flow boundary at the E and W - General head at N and S	10^{-4} –6×10^{-2}	55–4560	2.5–9.5	Water levels (5 wells)	731,268	2013–2033	30
El-Mansy et al. (2020)	El-Farafra	53.29	MODFLOW	- No flow at E and W - Constant head N (107 m) and S (96.2 m)	-	-	-	Water levels in 2015 (40 wells)	40,000	2015–2115	<40
Mahmodet al. (2013)	El-Farafra	163,688	GA	- A fixed boundary head with the flow direction from the SW to the NE	3.28×10^{-3} to 3.28×10^{-2}	50–500	-	Water level from year 1980 to 2005	-	2010–2060	29
Himida et al. (2011)	Bahariya	1,800	FEFLOW	- Constant head, N (100 m) and S (160 m) - No Flow at the E and W - Point of well discharge	-	-	-	Pumping test data from 1960 to 2000 and measuring head in 1999 (57 wells)	190,618	1999–2100	1.4–25.7
El Hossary (2013a, b)	Bahariya	10,767	Visual MODFLOW	-	0.8×10^{-1}–10^{-3}	250 and 3,700	4 and 20	Pumping test data and water levels from RIGW (2010)	651,640	2010–2035	3–26

Table 2 Summary of recent studies on groundwater management modeling conducted on El-Moghra aquifer during the past 10 years

Study	Location	Area modelled (km^2)	Code used	Boundary conditions	Input parameters				Water management simulation		
					Storativity (dimensionless)	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Data used for calibration	Simulated pumping discharge rate (m^3/day)	Simulated period start–end (year)	Predicted drawdown (m)
Youssef et al. 2012	Wadi El-Farigh	3,600	MODFLOW	Constant head boundary at the: - NE direction, 8 m - East range between 8 and 2 m - SW ranges between 16 and 20 m - West range between 20 and 22 m	1.2×10^{-4}–7.5×10^{-3}	95–3034	9.8–77.76	Water levels in November 1991 (contour map)	303,703	2006–2050	30
Khalifa 2014	Wadi El-Farigh	3,600	MODFLOW	Constant head boundary in the: - NE–SE direction, 4 m - SW with variable values between –16 and –22	0.027–0.135	95.04–3033.96	9.8–77.76	Water levels in 2006 and 2009 (5 wells)	569,020	2006–2050	17.23
Gomaa et al. 2021	Moghra Oasis	1,540	MODFLOW + MT3DMS (SEAWAT)	The Mediterranean Sea is considered to have a constant head boundary of 0 m, and a constant salinity boundary of 35,000 mg/L	0.1 and 0.001	760–7,600	1–24	Pumping tests 2018 (14 wells)	465,000	2018–2118	28–20
El Sabri et al. 2016	Moghra Oasis	0.075	MODFLOW	El Diffa plateau in the north is a no-flow boundary and the SW and NW sides act as general head boundaries	Not mentioned	Not mentioned	Not mentioned	Year 2013 (4 wells)	300,000	2040–2065	28
Sayed et al. 2020	Moghra Oasis	58,000	MODFLOW	-NE fixed head of 0 m -SW fixed head of –80 m (AMSL) -NW and SE, no flow	0.2	-	0.2 and 100	-	1,824,000	100 years (no dates)	139.7
Ragab et al. 2019	Moghra Aquifer	73,300	MODFLOW	Constant head at the: - Mediterranean Sea (0 m) - To the west parallel to Wadi El-Farigh the recharge rates from Rosetta branch, with head of 4 m and conductance of 936 m^2/day - Upward leakage from the artesian Nubian Sandstone Aquifer System in the SW direction of the Moghra Aquifer presents as a general head boundary with a conductance of 110 m^2/day	9.15×10^{-4}–0.25	419–3600	0.83–14.28	Water levels 1988 (contour map)	233.3×10^{6}	50 years (no dates)	369
Ahmed et al. 2015	Wadi El-Natrun (WEN)	2,016	MODFLOW	General head: - The first boundary condition (NW–SE) lies between the Pliocene–Pleistocene aquifer on the boundary aquifer of WEN Depression parallel to Cairo-Alex Desert Road -The second boundary condition (NW–SE) lies between the Pliocene-Miocene aquifer on the boundary WEN	1.85×10^{-4}–1.7×10^{-2}	500–1,660	9.8–38.9	Water levels in 2015 (14 wells)	56,428	2015–2065	3.29
El Osta et al. 2018	Wadi El-Natrun (WEN)	2,960	3D GMS hydraulic model	Head boundaries: - From the SW (–8 m), south (–12 m) and west (–14 m) - The eastern and NW parts are represented as no flow	1.8×10^{-4}	330–3,842	1.2–42.27	Groundwater levels of El Abd in 2005 and water levels in October 2015	289,972	2015–2050	40

Wadi El-Natroun is a depression to the east of El-Moghra Aquifer (Fig. 2b) with rapid and unregulated groundwater exploitation during the past two decades. Ahmed et al. (2015) used MODFLOW to simulate the current extraction rate (56,428 m^3/day) in this restricted area and predicted a drawdown of 3.29 m after 50 years. El Osta et al. (2018) tested higher rates of exploitation in the same year 2015 (289,972 m^3/day) and predicted a drawdown of 40 m in the year 2050. They proposed extracting 157,000 m^3/day, which can cause a drawdown of 4 m at the end of the simulation period in the year 2050.

Discussion

This paper reviews studies conducted using numerical models to examine the impact of development scenarios in the Western Desert of Egypt in the last 20 years. Comparisons between these studies yielded often highly diverging results. Several reasons can be identified. The first, and obvious, one is the limited availability of data in terms of physical and spatial description of aquifers, and the intensity and timing of abstraction. Tables 1 and 2 also illustrate differences between studies in terms of initially assumed storativity and transmissivity, but the values considered after calibration are never specified. Abstraction from wells is rarely comprehensively monitored and often derived from cultivated areas, averaged per well (e.g. El-Sheikh 2015). The differences between the wells (depth, capacity, etc.) are rarely known. With the exception of the works of Kato et al. (2012, 2014) on Dakhla Oasis, no author has taken on the burden of exploring changes in cropping patterns, cropping intensity or irrigation technology. This probably explains part of the variability in the abstraction/area ratio.

Modelling appears to be more dictated by the data available than by scientific excellence. Models were generally developed at a local scale for small areas and not the whole aquifer area due to lack of data—for example considering Wadi el-Farigh or the Qattara Depression rather than the whole Moghra Aquifer; thus, boundary conditions were often problematic. For the NSAS, the boundary conditions were selected based on assumptions about the regional groundwater flow direction and/or a fixed hydraulic head, while for El-Moghra Aquifer, studies used inconsistent head values and/or general heads to specify the boundary conditions (Table 2). Most of the studies assumed closed boundaries for their study area, i.e., the impact of excessive abstraction from one location to other adjacent areas in the same aquifer system and the interaction between aquifer systems on a regional scale were not examined.

For the NSAS, most of the reviewed studies used very limited data (e.g., Gad et al. 2011; Moharram et al. 2012), and only a few of them used historical data, limited however to a few wells in the study area, to calibrate their models (e.g., El-Sheikh 2015; Sharaky et al. 2019). The same applies to the El-Moghra Aquifer—the data used for calibration were limited, some studies using old contour maps (1988 and 1991) from the literature (e.g., Youssef et al. 2012; Ragab et al. 2019), while others used instant measurements of water levels in a limited number of wells which were insufficient to represent the whole aquifer system. Thus, studies conducted for the same area showed differing values of predicted water level drawdown for the same simulation periods (e.g., Youssef et al. 2012; Khalifa 2014).

None of the studies conducted a sensitivity analysis to test the change in the models' output values with the change in the input values, such as the assumptions of boundary conditions and the hydraulic parameters used. The accuracy of models is questionable, and the assumptions made to determine the boundaries, as well as the quantity and quality of field data used, can greatly affect the results. Therefore, it is important to use modeling as a complementary tool and not as a substitute for extensive field investigations (Wang and Anderson 1982).

Macro-level considerations also cast doubt on the accuracy of abstraction data. The planned reclaimed areas for the first phase of the mega reclamation project (4 million feddan) include 876,000 feddan (367,920 ha) in the Western Desert, i.e. ~4.38 BCM of groundwater, considering an average requirement of 5,000 m^3/feddan. Total groundwater extraction from the NSAS was estimated in 1998 at 0.95 BCM/year (USAID 1998). Since 1998, data about the total groundwater abstraction from the NSAS at a regional scale have not been shared and are mostly underestimated. Abdel-Shafy and Kamel (2016) estimated the extraction from the NSAS in the Western Desert at 1.65 BCM/year. The Ministry of Water Resources and Irrigation (MWRI 2005) estimated the total amount of deep groundwater extraction at 2.1 BCM in 2015 and was planning to double this amount to reach 4 BCM by 2037 (MWRI 2017). Meanwhile, the potential of groundwater abstracted from NSAS, to be used for development within the Western Desert, was estimated at 2.4 and 2.9 BCM by USAID (1998) and Sefelnasr (2007), respectively, within 100 years of exploitation. As groundwater is mostly allocated to irrigation, one can estimate total abstraction from the current cultivated areas. This study digitized the irrigated areas in the Western Desert in 2022 using Google Earth and found a gross area of 1,578,611 ha (3.78 million feddan; Fig. 3). Using a net/gross area ratio of 0.7 and the 5,000 m^3 per feddan per year average consumption rate considered by the Ministry of Agriculture and Land Reclamation for modern irrigation systems (drip and sprinkler), one can derive a minimum abstraction of ~13 BCM, which suggests that official data might be severely understating reality.

Another issue that emerged from the review is the lack of consensus on what constitutes a 'sustainability

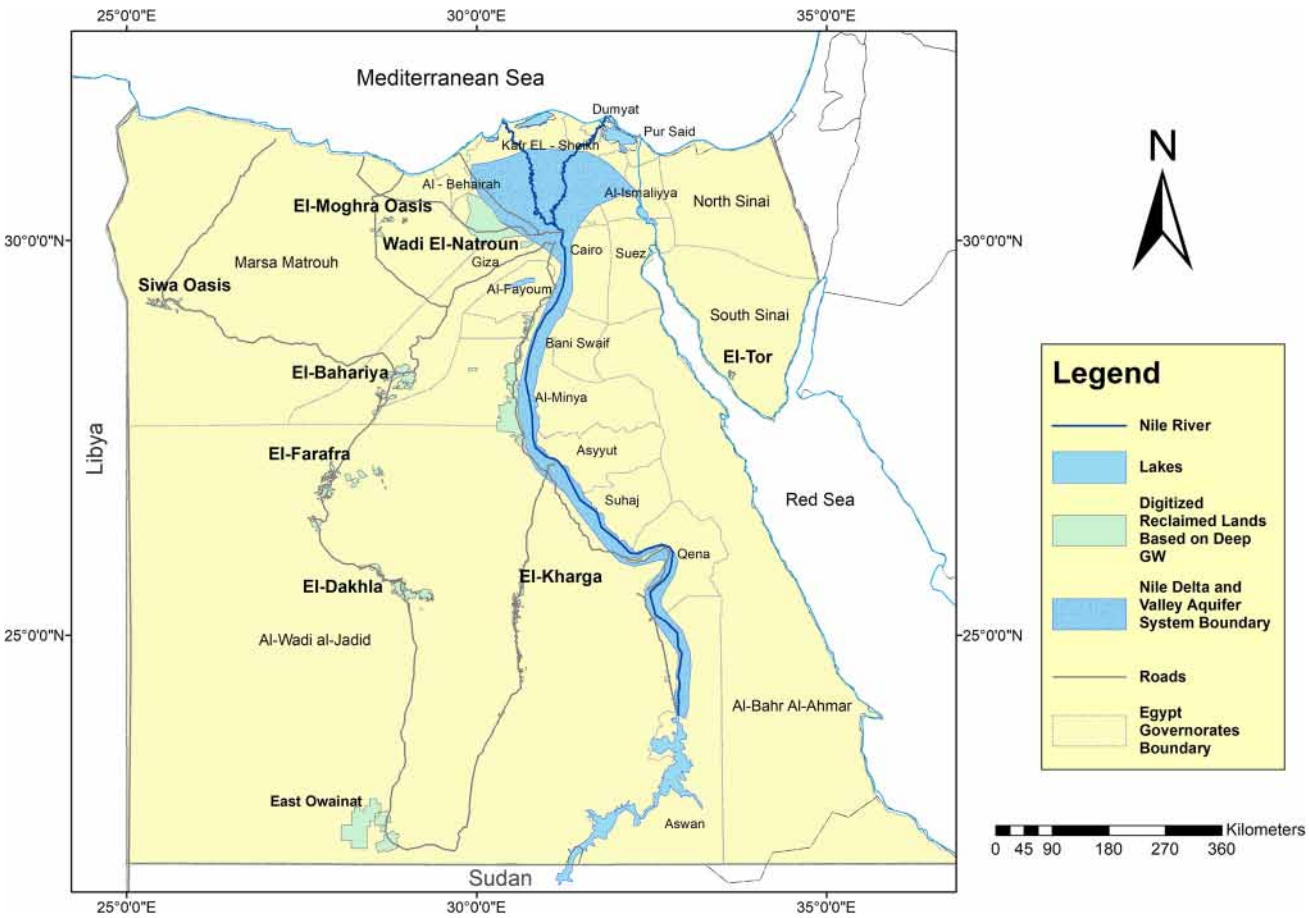

Fig. 3 Reclaimed lands based on deep groundwater (GW) abstraction in the Western Desert until 2022 (Source: digitized from Google Earth maps, 2022)

target'. Achieving the absolute sustainability of nonrenewable groundwater, such as the case of the NSAS, is not possible due to the very limited aquifer recharge; thus, 'sustainability' means arbitrarily limiting impacts in terms of drawdown within a certain time frame. Earlier studies for the NSAS defined a factor of safety for sustainable groundwater use as a drawdown that does not exceed 50% of the saturated thickness of the aquifer over 100 years (Hefny and Sahta 1996). Currently, the MWRI's conservative arbitrary limit, dubbed "safe yield" of groundwater abstraction, is defined as the extraction rate that causes a drawdown of 1 m/year (Sayed et al. 2020; MWRI 2018). According to El-Mansy et al. (2020), the MWRI adopted a sustainability criterion for Farafra Oasis whereby the economic lifting depth limit, set at 40 m beneath the land level, should not be reached before 100 years.

However, it is also clear that using the groundwater level as the only indicator of sustainability of groundwater management is misleading. Adverse impacts of such a drawdown, including an increase in groundwater salinity, decrease in natural flow from springs, and increase in pumping costs, were not considered. The increase in groundwater salinity (>1,500 ppm) in the El-Moghra Aquifer (south-west of Wadi Natrun) after 25 years of exploitation prompted investors to request Nile River water to secure their lands. A new canal (called the El-Mostaqbal Canal) fed by the Nile branch with a capacity of 7 MCM/day, in addition to a wastewater treatment plant with a capacity of 7.5 MCM/day, is currently under construction. The aim is to develop a 'New Delta' reclamation megaproject, announced in 2022, which could contribute to the recharging of El-Moghra Aquifer (Fig. 3b). It is noted that such a rapid constraint was anticipated by MWRI (2004), which expected salinity levels of extracted groundwater to increase threefold by 2030; however, this did not deter expansion in the area. Thus, sustainability of nonrenewable groundwater must also include water quality issues, as well as social and economic consequences in the short and long-term horizons (World Bank 2003).

In the early days, during the period from 1960 to the middle of 1995, water levels, piezometric heads and groundwater salinity data were collected every 3 months by the General Authority for Rehabilitation Projects and

Agricultural Authority (GARPAD) and the New Valley Development Authority (NVDA). Since then, the Ministry of Water Resources and Irrigation (MWRI) took over the responsibility of groundwater monitoring through the Research Institute of Groundwater (RIGW). RIGW established the National Groundwater Quality Monitoring Network (NGWQMN) in 1998 to collect water samples for hydro-chemical analysis, in addition to instant measurements of water levels, on a yearly basis from production and observation wells at depths ranging from 1,200 to 50 m, mostly located in the Nile Delta and Valley area, in addition to a few deep wells located in the Western Desert. Recently, the MWRI imposed the construction of one observation well every 420 ha at the expense of the private sector under the supervision of the Groundwater Sector of MWRI, which also has its own data. Currently, datasets are not shared and are difficult to access, because the government considers them as national security information. Therefore, most researchers depend on personal contacts and/or collecting instant data from few productive wells in their study areas, in addition to wells owned by the private sector (eg. petroleum exploration companies). The cost of installing an observation well in desert lands is high ($100,000 per well) and protecting it from theft is difficult. The integration between the Gravity Recovery and Climate Experiment (GRACE) satellite data and data-driven models using Artificial Neural Networks (ANNs) to predict groundwater levels could help overcome the problem of data availability (Yin et al. 2021).

Two threats loom large, with the first being the high potential impact of climate change, which was not considered in the planning for such megaprojects. Recent studies show an expected increase in temperature in Egypt in the near future and there is a call for adaptation of plans (Hamed et al. 2022). Gado et al. (2022) expected an increase in the average temperature of 4.08–7.41 °C by the end of the century, with the Western Desert, Upper Egypt, and southern Sinai Peninsula as the most affected regions, which will lead to a substantial increase in potential evapotranspiration rates and crop water consumption. Second, increasing the use of solar energy for pumping groundwater is also likely to remove the energy constraint and to accelerate the depletion of the aquifers as experienced in many areas worldwide, e.g. traditional oases in southern Tunisia (Mekki et al. 2021).

Conclusions

Even though groundwater reserves play an important role in water security, they are still poorly managed and monitored in many countries worldwide (Molle and Closas 2017). Groundwater levels have dropped dramatically in many countries due to excessive development of agricultural lands (Famiglietti 2014). In Egypt, the political will to reclaim desert lands despite limited resources puts pressure on groundwater reserves. Therefore, there is an urgent need for a national research strategy aimed at producing an effective and sustainable plan for the use of this limited resource for now and in the future.

This paper reviewed the studies conducted in the last two decades for modeling the aquifer systems in the Western Desert of Egypt to identify the knowledge gaps, limitations, and advice for future research. Comparisons between modeling studies and their model parameters, calibration data, time horizons, and outputs revealed a stunning lack of convergence. Most studies modeled local areas and only used limited data to feed and calibrate their models. Also, assumptions regarding the conceptual models, the size of the area considered, boundary conditions, or hydraulic parameters affected the results and recommendations for every single aquifer. Only one study delved into understanding changes in terms of agricultural dynamics, cropping patterns, or irrigation technology.

Sustainability targets also differed greatly. Although the Western Desert only has very marginal recharge and 'sustainability' is therefore equated with an arbitrary limit in terms of time and/or overall abstraction, this multiplicity opens the door to unspecified futures, with no standard against which judgment can be made on what is desirable or excessive. It also clearly appeared that the focus on the drawdown of the water table was missing the degradation in water quality, which often comes with drawdown. Very few studies consider the two dimensions together.

The first implication is straightforward and unsurprising: more in-depth investigation is needed to better describe the spatial heterogeneity of the hydraulic parameters, characterize the temporal and spatial dimensions of groundwater abstraction, include water quality aspects, and carry out uncertainty and sensitivity analysis, including not only hydraulic parameters but also the assumptions made in terms of targets, boundary conditions, or other factors that affect the accuracy of modeling, such as the recharge terms of El-Moghra aquifer system and the connection between different formations within the same aquifer and between different aquifer systems.

All this is predicated upon the provision of an adequate data set for constructing reliable hydrogeological models. Studies conducted on a regional scale that took into consideration the interaction between aquifer systems and climate change within the framework of current and future development plans are missing, due to the unavailability of data, access difficulties, and high costs of collecting such data in desert lands. Setting up an open-access national water information system including all aquifer systems and their characteristics, spatial and temporal monitoring

data of groundwater levels and quality, land levels, and climate variability would form a basis for all researchers to enhance their work.

Developing and formulating sustainable plans that meet the social, economic, and environmental needs of communities is becoming urgent as megaprojects are developed and more and more desert land is reclaimed. This should include clear sustainability targets and the definition of undesirable results, minimum thresholds, measurable objectives, and an exit strategy in case any undesirable effects appear. Available knowledge, this review has shown, is far from sufficient to inform these plans. The responsibility for planning, implementing, and monitoring sustainable groundwater plans should also be clearly defined by law for both government and users to ensure effective implementation and sustainable management for conserving the rights of the generations to come.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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