OPTIMUM STRATEGIES FOR SUSTAINABLE FOSSIL GROUNDWATER RESERVE UTILIZATION IN EGYPT

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ABSTRACT

Egypt is standing at a critical juncture regarding the availability of adequate water supplies to satisfy its development plan. As a follow-up, a strategy hereby groundwater would contribute to covering the increasing water demands for all purposes through abstractions from numerous pumping wells has been adopted. There is a crucial need for such extensive groundwater abstraction to fulfil the water deficit that would be exacerbated under the increasing population growth rate; However, lack of and mismanagement of groundwater exploitation jeopardize the aquifers to depletion and/or deterioration. Thus, it is of utmost importance to manage these aquifers to promote a sustainable groundwater supply, avoiding overexploitation that bears negative impacts. Given their predictive capability, simulation models often offer a viable means for providing input to management decisions, as they can forecast the likely impacts of a particular water management strategy. This work presents a comprehensive review of the simulation modelling applications for the management of nonrenewable groundwater reserves in Egypt. It intends to measure Egypt's groundwater resources management status based on readily available information from related research articles. It thereby demonstrates the need to frame a rational strategy for the long-term sustainable exploitation as well as restoration (quantity and chemical quality) of the Egyptian aquifer systems. Conclusions are drawn where gaps exist, and future research is suggested to obtain a regional groundwater framework directive.

Keywords: Modeling, Moghra aquifer, Agribusiness, Over-pumping, Depletion

1 INTRODUCTION

Egypt’s imminent water problems will aggravate during the next few years due to increasing demands for municipal, industrial, and agricultural activities. Moreover, the upstream dams will entail a reduction in the Nile river discharges during their filling and operation stages (El-Nashar & Elyamany, 2018). Egypt will not be able to withdraw sufficient water supplies to meet its public needs (Sallam, 2018). Thus, Egypt must adopt an integrated water resources management approach to promote its limited water resources' coordinated development and management. Moreover, it becomes inevitable to search for additional available water resources. The government of Egypt has initiated an ambitious strategy hereby groundwater has contributed to covering the increasing water requirements for all purposes (Elnashar, 2014).

In the context of the expected water budget deficit, Egypt shall witness a key challenge for the agriculture sector to feed its growing population (Shalaby et al., 2011). Accordingly, a development project, along with plenty of megaprojects, is advocated to increase the cultivated areas by 4 million acres interspersed throughout the drylands of Egypt, Figure 1. The Egyptian government has undertaken agricultural strategies starting with 1.5 million acres in 2016 (NIWR, 2017). The project will be implemented to move towards horizontal expansion in the new lands in the desert. Thus, they mostly (90%) depend on the Nubian Sandstone Aquifer's nonrenewable groundwater and the Moghra aquifer, Western Desert, Egypt. The groundwater withdrawal in the Egyptian desert lands was considered a promising additional conventional water resource (EGDC, 2016). Currently, the use of pumped groundwater is well underway in the newly cultivated areas mainly for irrigation, but also for domestic needs, and the pumping of groundwater is projected to increase in a year in a year out. Considering groundwater as the sole source of freshwater in these lands would shift the dynamics of aquifers, especially under the scarce water conditions, which is an essential constraint to development.

The insufficient or non-renewability of these two aquifer systems (e.g., the Moghra aquifer and the Nubian sandstone aquifer) in Egypt poses more complexity in their management. However, there is still considerable room for utilization of this resource provided principles of rationality. In this context, numerical groundwater modelling is the most sophisticated method that may help investigate such complex systems in terms of non-renewability and water demand. This article proceeds by reviewing the nature of problems emerging due to groundwater resource mismanagement and the available numerical codes to help. In the rest of this article, studies that involved the development of groundwater models to solve flow and transport in the two desert aquifers were reviewed. The review focuses on more studies related to a specific problem in groundwater modelling and management of fossil aquifers. The report then discusses the identified knowledge gaps and suggests some strategies and options that will be important in research and policy to promote exploiting these resources. As far as we know, this is the first review dedicated to groundwater modelling in Egyptian fossil aquifers.

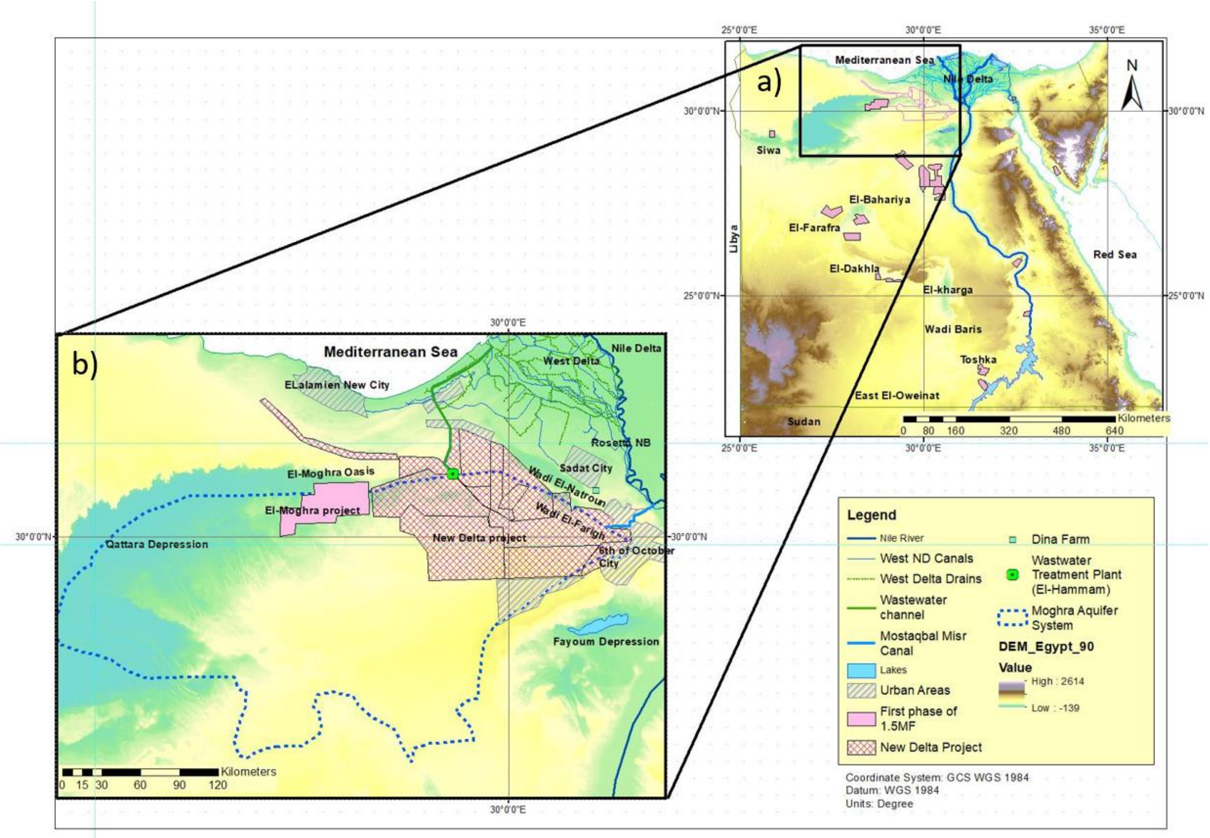

Figure 1. a) Location map of the 1.5 M acres project, b) Location of the New Delta project and the Moghra aquifer

2 OVERVIEW OF MAJOR FOSSIL AQUIFERS IN EGYPT

In Egypt, six aquifers have high potentiality for exploitation, as shown in Figure **2**. This study is concerned with the two majors' unrenewable aquifers (i.e., the Moghra aquifer, and the Nubian sandstone aquifer) where groundwater is exploited on a large scale. The characteristics of deposits formation of these aquifers are described in the following:

1) The Moghra aquifer in the north of the Western Desert, a mixture of renewable and fossil water, covers the Moghra desert area at the western edge of the Nile Delta with an area of 50,000 km^2 (El Tahlawi et al., 2008). The aquifer consists mainly of Miocene fluviatile and fluvio-marine gravel and coarse sand sediments with clay and siltstone intercalations (Sayed et al., 2020). The aquifer depth reaches up to 900 m in the centre and decreases towards the north and west, where its base is in line with the ground level (Gomaa et al., 2021). The aquifer is marginally replenished, with low water quantities, specifically from (i) the Nile Delta aquifer through seepage, (ii) the overlying aquifers (Miocene limestone aquifer and Nubian Sandstone Aquifer System) through upward leakage, and (iii) a minor contribution from rainfall through infiltration. The main aquifer discharge source is evaporation from local depressions (i.e., Qattara in the west and Wadi El-Natroun in the east) and by lateral seepage into carbonate formations (Abdel Mogith et al., 2013; Morad et al., 2014). The aquifer water salinity ranges, from slightly brackish (1,000 ppm) within a narrow wedge in the vicinity of the Nile delta to saline (up to 12,000 ppm) over the rest of the aquifer's area (Eltarabily & Moghazy, 2021). The Moghra desert is one of the areas selected for the national land reclamation project that was inaugurated in late 2015. Around 200 Mm^3 of water will be annually abstracted to sustain ongoing cultivation and fish breeding activities (Sayed et al., 2019).
2) The Nubian sandstone aquifer cover most (83%) of the country's whole area (Sharaky et al., 2019). The aquifer occurs in central and northern Egypt, confined by a thick Upper Cretaceous shale deposit separating it from fissured carbonate aquifers (Figure 1). It overlays the Proterozoic basement rocks, and its total thickness ranges from 0.5 to 4 km (Aly et al., 2019). The aquifer system is composed mainly of Paleozoic and Mesozoic sandstone, intercalated by pre-Upper Cretaceous clay and shale deposits (Aly et al., 2019). It consists of two major formations (i.e., the post-Nubian and the Nubian reservoirs) separated by a low-permeability layer (i.e., aquitard). Its groundwater quality is relatively good: fresh (total dissolved solids (TDS) less than 1,000 mg/L) in the Western Desert, slightly brackish (1,500 < TDS < 2,000 mg/L) in the Sinai Peninsula and brackish (3,000 < TDS < 4,000 mg/L) in the Eastern Desert (Elmansy et al., 2020). It is a high-potential aquifer in Egypt, water stored in the aquifer is about 40,000 km^3 of paleowater (CEDARE, 2014).

In the southern portions of the Western Desert, sandstone outcrops expose, and the aquifer is unconfined. This has fostered extensive development to have occurred in the southwestern part of the country, where this study scope is. Originally, the aquifer in this region supplied the New Valley Oases (Kharga, Dakhla, Bahareya, and Farafra) through free-flowing springs and tube wells. These shallow wells have run dry since 1960 and have been replaced by deep wells that were installed for the extensive irrigation project that was developed in the vicinity of old oases as well as "East Oweinat", and "Darb El-Arbain" areas. The cultivation area steadily increased to reach 4,200 ha in 2003 with an estimated total annual extraction of 2.8 Km^3 (CEDARE, 2014). By 2015, the extraction rate has increased by 500% (Ebraheem et al., 2002). Consequently, groundwater levels have fallen over the last 40 years by 60 m within the wells fields (El-Rawy & Smedt, 2020). According to the recently released national groundwater management policies, large cultivation schemes are being developed in this region where the Nubian aquifer's role has been emphasized.

The Cretaceous Nubian Sandstone is the main aquifer within the desert of the Sinai Peninsula. Its depth varies from 100 m in the central portion to 500 m in the south (Ahmed, 2020). Surface recharge, from rainfall, occurs over zones of sandstone outcrops at the mountain's foothills and fractured depositions (Balderer et al., 2014). The Mediterranean Sea in the north and the Red Sea’s gulfs in the south (i.e., the Suez gulf to the west, and the Aqaba Gulf to the east) represent naturl effluents of the groundwater reserves of the Sinai Peninsula (Ahmed et al., 2022).

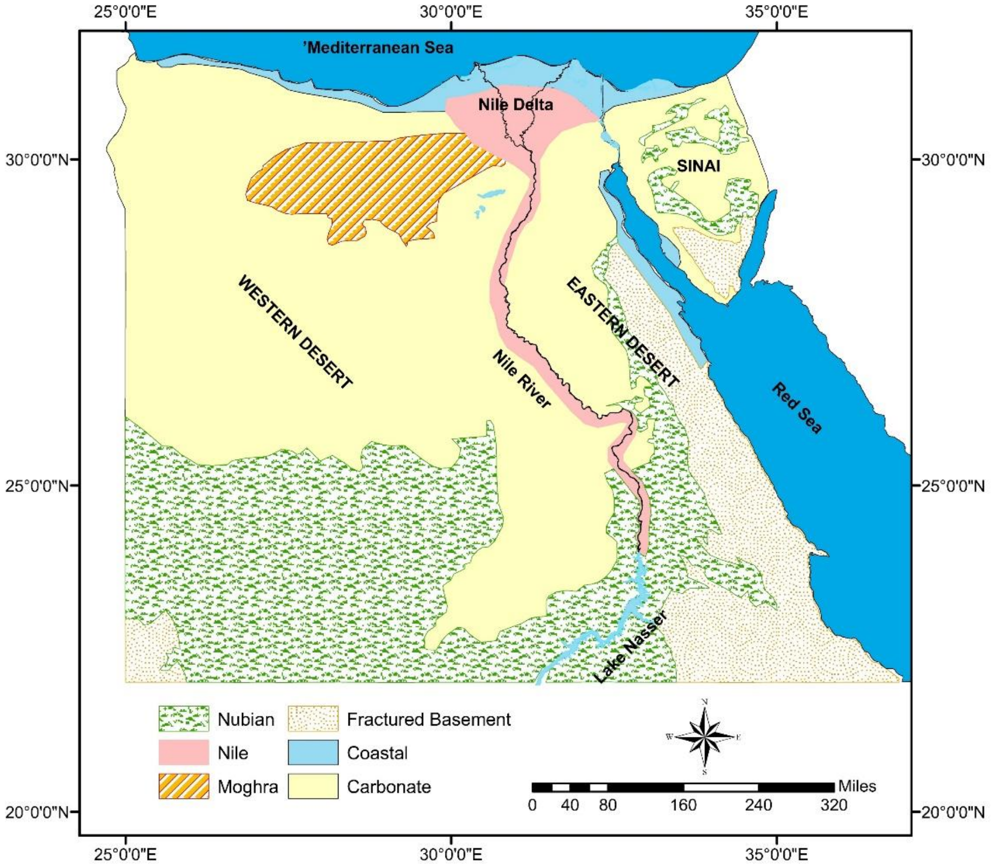

Figure 2. Spatial distribution of the physiographical regions and the major aquifer systems in Egypt

3 IMPLICATIONS OF MISMANAGEMENT OF GROUNDWATER PUMPING

The deficiency of groundwater exploitation is a major constraint for developed and developing countries' economic development (Singh, 2014). Development-induced environmental impacts have appeared in many countries of the world. However, these impacts are subtle in some regions and dramatic in others, causing interconnected groundwater management problems. Lack-or mismanagement of groundwater resources is exerting negative impacts on the quality and availability of groundwater resources. Intensive utilization and over pumping through the wells system may lead to water quality degradation and extensive drawdown of water levels of operational wells. Thus, a balance needs to be established between groundwater recharge (aquifer replenishment) and water extraction.

Overexploitation higher than the aquifer recharge results in a decline in groundwater level, which might lead to some adverse consequences like limited availability of groundwater, land subsidence, and decline in surface vegetation, etc. Salinization (salinity invasion) of local coastal aquifers is also a common issue in areas where over-abstraction of groundwater occurs (Hussain et al., 2019). This malpractice of uncontrolled pumping is further exacerbated to meet the increasing water demand for both domestic and agriculture and is particularly evident in arid-and semi-arid countries. Overdraft is a common issue in the development of fossil (nonrenewable) aquifers for intensive agricultural practices. To fulfil the cultivation requirements, highly increased pumping of groundwater is taking place and a concentrated number of wells that are not spatially distributed over wider areas are being established.

For instance, illegal pumping through concentrated wells in several areas throughout the Eocene aquifer in West Bank, Palestine has consequently declined /depleted the groundwater levels up to 110 m from 2000 to 2017 and many of these wells were dried up (Almasri et al., 2020). These consequences have become a striking reality causing a set of interconnected groundwater management problems. Deterioration of groundwater quality from over-pumping and seawater intrusion is limiting the amount of available sustained groundwater in this area causing a potential crisis for the local economy. Thus, effective planning and management of groundwater resources are of high importance. Only If this resource is managed in an efficient way considering sustainable utilization, it will have the potential to meet the long-term increasing water demand.

4 NUMERICAL MODELS AS TOOLS FOR GROUNDWATER MANAGEMENT

Groundwater management involves identifying the optimal locations, timing, and rate of water extraction, and controlling pollution transport into the aquifer. The extraction rate from the aquifer can be estimated just by computing the aquifer's water balance. In this regard, a fundamental concept (safe yield) to quantify the possible sustainable development of a groundwater basin is formatted. Safe yield is defined as the attainment and maintenance of a long-term annual balance between the amount of groundwater withdrawn and the amount of recharge (Alley & Leake, 2004). With intensifying water insecurity around the world and to satisfy the increasing water demand, more detailed spatially and temporally distributed pumping strategies are required. A need to emphasize the significant role of and challenges related to groundwater management that should not be excluded from integrated approaches has been raised. Thus, the state of art mathematical model has the opportunity to determine the best pumping strategy among different alternatives. Nowadays, the typical approach to manage groundwater resources has become to develop, calibrate and validate a 3D or quasi-3D finite element or finite difference groundwater model, and run it under plausible scenarios of change by adjusting the boundary conditions influenced by land use, namely recharge, evapotranspiration and pumping, for assessing trade-offs among potential water pumping scenarios, and in diagnosing the drivers of aquifer depletion and changes in water quality. Moreover, they are used to domesticate seawater intrusion by managing the discharge from the aquifer. The migration rate of seawater intrusion may be reduced by thoroughly investigating and planning new management policies for optimal pumping rate. Table 1 lists the popular mathematical codes used in the fields of groundwater modelling. However, most studies surveyed in this report have adopted Mod flow for groundwater flow simulating and MT3D for contamination fate and transport. Few studies utilized the finite-element-based model called Feflow. In general, Groundwater flow models can be divided into three main types:

1- Interpretive: used as a framework for studying system dynamics and/or organizing field data. It does not necessarily require calibration.
2- Generic: used to analyze flow in a hypothetical hydrogeologic system. It may be useful to help frame regulatory guidelines for a specific region and does not necessarily require calibration.
3- Predictive: used to predict the future. It requires model calibration and thereby sufficient observational records to support the calibration of the model over a range of conditions. The transient simulations are used to test the aquifer response to supposed operational scenarios. While coupling a steady-state groundwater model with an optimization model adopting the response matrix approach or linear programming yields more feasible and resilient results achieving multiple development objectives simultaneously (Lobato & Steffen, 2017; Peralta & Kalwij, 2012).

5 MANAGING FOSSIL AQUIFERS FOR NEW DEVELOPMENT PROJECT

Over the past 20 years, researchers have developed some models to study the effect of some proposed local projects depending on groundwater potentialities of the desert aquifers. The developed program is mostly executed to show the effect of extractions scenarios on the groundwater potentials. Results of simulations show either insignificant effect on the groundwater potentials in a specific aquifer system or a remarkable lowering in the groundwater potentials. Few studies were carried out on these aquifers to optimize groundwater extraction. The main findings of these studies are summarized in the following sections.

Table 1. List of the commonly used numerical codes for groundwater modelling.

Code Name	Features	References
JHU2D	Solving a transient two-dimensional flow and heat transport using a finite element approach	Garven & Freeze (1984)
SUTRA	Solving a two-dimensional variable-density flow and solute or energy transport in variably saturated media using a finite element/a finite difference approach	Voss (1984)
OILGEN	Solving a steady-state two-dimensional flow and heat transfer using a finite element method	Garven (1989)
UNSATCHEM	Solving one-dimensional water flow, heat transport, carbon dioxide transport, and solute transport with major ion equilibrium and kinetic chemistry in variably saturated media	Simbnek et al. (1996)
MT3DMS	Solving three-dimensional multispecies transport (advection, dispersion, and chemical reactions) of contaminants in groundwater. The flow is derived from MODFLOW results	Zheng & Wang (1999)
MODFLOW	Solving a two- and three-dimensional groundwater flow by a finite difference method	Harbaugh et al. (2000)
MEL2DSLT	Solving an aerial model of vertically averaged flow and transport	Sorek et al. (2001)
FEAS	Solving variable-density flow and transport using a finite elements approach	Zhou et al. (2005)
Hydrus 1D	Solving flow, heat, and solute transport in one-dimensional variably saturated media	Rassam et al. (2018)
FEFLOW	Solving variable-density flow, mass, and heat transport in two- and three-dimensional for variably saturated media	Dierschg (2013; Trefry & Muffels (2007)
AKCell	Solving mass balance for a cell model of an aquifer	Kessler & Kafri (2007)
Hydrus 2D/3D	Solving flow, heat, and solute transport in two and three-dimensional variably saturated media using a finite element approach	Šimůnek et al. (2016)

5.1 The Moghra Aquifer

The Moghra aquifer extends from the western boundaries of the Nile Delta to Qattara Depression and southwards to El-Fayoum Depression with a total surface area of about 50,000 km^2. There are various sources that recharge El-Moghra aquifer; (i) seepage from the western part of the Nile Delta aquifer, (ii) flow from the overlying Miocene limestone aquifer, (iii) upward leakage from the deep Nubian Sandstone Aquifer System (NSAS) and (iv) minor contribution from rainfall. Aquifer discharge occurs through evaporation in Qattara and Wadi El Natroun depressions and lateral seepage into carbonate rocks of the western part of Qattara Depression. So Moghra aquifer's water is a mixture of renewable and fossil water. The annual extraction from this system until 2015 was approximately 200 Mm^3/year less than the recharge quantity and the surplus water flows northward. Thus, a potential for further utilization of the aquifer was advocated in 2015. A set of studies testing different policies and several development plans has been undertaken to prevent aquifer depletion.

Ragab et al. (2019) invoked the Visual Modflow software to examine the effect of different pumping policies from the Moghra aquifer during the upcoming 50 years. The model domain consists of one layer that is discretized by 75 ×100 grid cells of an area of 25 km^2. Two recharge sources from the Nubian aquifer and Rosetta River branch were modelled as general head boundaries while the Mediternean Sea was inputted as a constant head boundary. Four pumping rates from 3,550 wells were supposed. The first two scenarios involve water extraction at a rate of Q =180 and 90 m^3/d/well (total discharge = 233×10^6 and 117×10^6 m^3/year) which have caused a depletion of the aquifer in some areas. While the third pumping scenario at the rate of Q/well = 54 m^3/d/well (total discharge = 70×10^6 m^3/year) has induced a drawdown up to 165 m. Eventually, the authors evaluated a scenario of operating the wells at two different withdrawal rates (Q/well =180 m^3/d for the wells in the northern portion & 54 m^3/d for wells close to the Nubian aquifer), a uniform reduction in water elevation has resulted and was estimated by about 350 m. Sayed et al. (2020) investigated the Moghra aquifer's capabilities in supplying water for new cultivation areas. The MODFLOW/GMS software was used to mimic the aquifer system that was modelled by a domain of one-layer and square grid cells of 1000 m length. Two Dirichlet boundaries were defined with fixed head values represent the Mediterranean Sea to the north and the Qattara Depression to the west. The model was calibrated under steady-state conditions. Three well combinations; (e.g., 440, 1000 and 1520 running on a fixed rate of 1200 m^3/day/well) were explored. The maximum drawdowns after 100 years were computed as 52, 92, 140 m respectively. The authors concluded the total area for reclamation shouldnot exceed 85,714 acres (360 km^2).

5.2 Nubian Sandstone Aquifer

The Nubian Sandstone Aquifer System (NSAS) is a closed transboundary groundwater aquifer in the Eastern Sahara of Africa occupied an area of about 2.35 million km^2 shared among Egypt, Libya, Sudan, and Chad. The NSAS is a non-renewable groundwater system of high volume that reaches about 212x10^3 km^3. During the past three decades, Egypt, Libya, and Sudan have made separate attempts to develop and utilize the NSAS and the overlying desert lands. Each country thus has its specific experiences, motivations, and success in that field. In Egypt, most of the present water extracted from the NSAS was used for agriculture for farms located in old traditional oases in Egypt (New Valley). Recently, the government has decided to extend the land reclamation activities into vast and isolated desert areas, based on the utilization of the available groundwater resources of the NSAS. The new reclamation project will be carried out in three subphases in nine areas of the Western Desert, including Toshka, Farafra Oasis, Dakhla Oasis, Bahariya Oasis, West Minya, and East Owainat. Thus, the rational exploitation of the aquifer water was the objective of the studies in Table 3. Sharaky et al. (2019) constructed a conceptual model to determine the possibility of cultivation expansion in Toshka area depending on groundwater. Different operation scenarios considering the daily Sunrise hours and the pump capacity that simulate the water flow system through 100 years were evaluated. The results demonstrated that the safe water use is to pump 1,007 m^3/day from 102 wells which is sufficient to provide a total of 25,000 feddans assuming a water duty of 1,500 m^3/feddan/year. Elmansy et al. (2020) obtained the local depression in groundwater potentiometric level associated with different extraction rates surveying the proposed reclaimed area of 10,000 feddan in Sahl Baraka, Farafra oasis. Five extraction rates (e.g.,40,80,120,160, and 200 km^3 from 40 wells) were simulated, and all have resulted in a sustainable drawdown after 100 years. The Benefit-Deficit analysis for economic lifting depth criteria was applied to obtain the most beneficial extraction rate that was concluded as 3000 m^3/day/well. Moharram et al. (2012) combined the application of MODFLOW with Genetic Algorithm (GA) techniques to develop the optimal pumping rate in El-Farafra Oasis. Three different development plans of 10500, 12500, 14500 acres were proposed. The results can be summarized as the optimal pumping rate was 183023, 220016, and 254484 m^3/day. Himida et al. (2011) utilized Feflow numerical model to assess groundwater potentiality for new development in the Bahariya Oasis. A gradual increase in the current groundwater withdrawal rate ($34.8x10^6$ m^3/year) by a range from 10% to 100% was applied. The resulted drawdowns were safe and economic for the next 100 years. Further run was simulated to obtain the yield achieving 100 m drawdown in the next 100 years as recommended by the MWRI.

Table 2. Comparison of recent studies on groundwater management modeling conducted on EL-Moghra aquifer during the past 10 years.

Study	Location	Code Used	Calibration Data	Simulated Pumping Rate (m^3/day)	Simulated period. (Years)	Predicted Drawdown (m)
Youssef et al., 2012	Wadi El-Farigh	MODFLOW	Water levels 1991 (Contour map)	303703	44	30
Khalifa, 2014	Wadi El-Farigh	MODFLOW	water levels 2006 (5 wells)	569020	44	17.23
Gomaa et al., 2021	Moghra Oasis	MODFLOW+ MT3DMS (SEAWAT)	pumping tests 2018 (14 wells)	465000	100	28 to 20
El Sabri et al., 2016	Moghra Oasis	MODFLOW	Water levels 2013 (4 wells)	300000	50	28
Ragab et al., 2019	Moghra Aquifer	MODFLOW	Water levels 1988 (Contour map)	$233.3x10^6$	50	369
Ahmed et al., 2015	Wadi El-Natrun (WEN)	MODFLOW	water levels 2015 (14 wells)	56428	50	0.76 to 3.29
El Osta, 2018	Wadi El-Natrun (WEN)	3D GMS hydraulic model	water levels 2015	289972	35	37

A great extraction rate (837357 m^3/day) satisfies for irrigating 52335 feddans (i.e., 54428 acre) was reported. El Osta (2018) investigated local implications of three operation scenarios represent the present and future stresses over a 30-year period on groundwater within the Paris–Abu Bayan area. The results demonstrated the need to reduce the water withdrawal by approximately 25% by applying modern irrigation systems to avoid the large decline in water levels.

SUMMARY AND CONCLUSIONS

This article reviewed about 30 studies that developed and utilized numerical models (shelf codes) to solve flow and transport problems in Egypt's desert groundwater reserves. The review was focused on works published during the last two decades when clear attention to groundwater has been given. However, a shifting trend in the publication is pointed in the last five years, supported by the surface water scarcity and the national plan to behold groundwater as a solution. About 80% of the reviewed studies were advocated to simulate flow aquifers, in which MODFLOW was the most popular software adopted in 18 research. MT3DMS package involved in SEAWAT code was utilized in 6 studies for transport. Few (4 of 30) studies used the FEFLOW code in either the flow or transport modelling. All studies for saltwater intrusion have adopted the boundary layer approach for modeling transition zone between freshwater and saltwater. Only two studies have integrated the mathematical models with optimization approaches (e.g., Gad & Khalaf (2015); Moharram et al. (2012) to address the optimal groundwater management of the exploited aquifers for multiple objectives. All studies' results significantly impacted the development and utilization of groundwater resources in Egypt. Considering the complexity of the problems involved, these studies will continue to be an important tool for increasing our understanding of the flow and transport in the studied aquifers. This improved understanding is essential to provide the underpinning for sound local water management decision-making that will balance our country's environmental protection and socio-economic welfare.

However, some studies have not succeeded to provide a reliable decision-making. A common concern of these studies is the scarcity of used time series to develop such groundwater models as rigorous modeling exercises, and accordingly, they may not be deemed as aquifers management decision making. Datasets of hydrologic, climatological, and geological required as initial inputs to run and steady-state calibrate groundwater models are of poor or unknown accuracy and may also contain significant gaps. While the data required for transient scenario development are not readily available. Assuming these data exist in some cases, they often contain sparse records. Using them in model development becomes a key challenge, even when adopting common interpolation and infilling methods. Data presenting heterogeneity in hydraulic properties is lacking and thus it is not warranted to incorporate heterogeneity in the modeled layers. Homogeneous conditions are assumed to prevail in each of the different formations modeled and the spatial. As a sum up, lack of required data or restriction with its sharing and access, have resulted in the creation of groundwater models being unconvincingly validated or incompletely conceptualized.

Many studies have been conducted to set long-term goals of the reclamation projects depending on pumped groundwater from nonrenewable aquifers (Moghra and NSSA) through shallow wells. Considering their finite character and the uncertainties regarding their quantity and lifetime, their sustainable management has become extremely crucial for viable development in agricultural expansion areas. Yet no withdrawal policy or discharging constraints from such aquifers with low replenishment capacity were set. The traditional groundwater sustainability concept of discharge equals recharge for these fossil aquifers is not applicable. In Moghra aquifer, as groundwater extraction increases, the volume of groundwater storage decreases (Ragab et al., 2019; Sayed et al., 2020). Consequently, the groundwater potentiometric level decreases. Also, in NSSA a cone depression around the stressed areas was concluded. Given the pumping cost associated with the lifting depth, restrict groundwater allocation to those areas and rates resulting in added value from water is highly recommended. Accordingly, the concept and criteria of groundwater sustainability should be differently standardized and evaluated, and the Egyptian relevant institutions must set the groundwater sustainability criteria for the new development areas since the pumping of groundwater under traditional sustainability definitions and criteria is not sustainable. Such required groundwater sustainability is not possible without monitoring, characterizing, and evaluating the performance of these aquifers' management scenarios. Herein, the pumping strategies developed within the reviewed studies could be used by the water management authorities directly to sustainably manage the groundwater resources of each development area. Their outcome will also be helpful for

Table 3. Summary of the studies investigated the groundwater development potential of the NSSA in the Western desert, Egypt.

Study	Study Area	Management Scenarios	Software	MODEL	Main findings
Sharaky et al. (2019)	Toshka area	Four pumping rates from 102 wells (e.g., 3357, 2,686, 2,014, and 1,007) m^3/day/well	Visual MODFLOW	One layer (40 × 40 × 275 m)	Safe water use is to pump 1,007 m^3 from each well in 8.4 operation hours. Max. drawdown is 15 m after 100 years
Elmansy et al. (2020)	Sahl Baraka, Farafra oasis	Five extraction rates from 40 wells (e.g., 1000, 2000, 3000, 4000, and 5000) m^3/day/well	MODFLOW	Three layers 146 × 146 ×50 m	Extraction rates Q_{well} = 4000 and 5000 m^3/d are not sustainable from the economic lifting depth Q_{well} = -3000 m^3/d is the most beneficial according both duration and economic lifting depth
Moharram et al. (2012)	El-Farafra Oasis	Three development plans based on pumping from 48, 58, and 68 wells	MODFLOW with GA	One layer 50 × 60 ×737.3 km^2	For Sc.1, Optimal rate =183023 m^3/day For Sc. 2, Optimal rate = 220016 m^3/day For Sc. 3, Optimal rate = 258007 m^3/day
Himida et al. (2011)	Bahariya Oasis	Three main operation policies for 100 years Current, Constant rate = 34.8x10^6 m^3/year Promising, Rates = 38, 44, 52, 75, 68 Bm ^{3} /year Safe rate to obtain drawdown = 100 m	FEFLOW	NA	The groundwater potentiality in the Bahariya Oasis is very high, and the agricultural development is highly recommended
El Osta (2018)	Paris–Abu Bayan area	Three management scenarios were applied on the calibrated model to display the present and future stresses on this aquifer over a 30-year period (2012–2042).	MODFLOW	2665 cells (65 columns, 41 rows), an area of 1 km^2	The results demonstrated the need to reduce the water withdrawal by approximately 25%

the planning and establishment of the new well field to meet the increasing demand for water due to population growth and anticipated climate change.

This review may support assigning a safe and recommended yield, ensuring water supply fulfills the water demand for agriculture and industries, and simultaneously protecting the environment by limiting the groundwater drawdown to a certain threshold. However, to set long-term goals of sustainable exploitation, it is recommended to implement a monitoring system to assess the periodical impact of the proposed developments and update a national geodata set. Reliable estimates of groundwater abstraction and automatic well control system should be done. Water managers, local communities, and hydrogeologists should work together to devise policies and adapt future measures to achieve long-term sustainable goals. Likewise, there is a crucial need for the assessment of the economic return of the planned reclamations projects considering both duration and lifting depth. Moreover, it can be stated a general recommendation to increasing public awareness for proper use of groundwater resources. In addition, rainwater harvesting, and desalination of both saline and brackish water are recommended alternatives for increasing water resources in Egypt. Rainwater harvesting (RWH) can be considered a sustainable adaptation measure that could cover supplemental needs of domestic water and overcome both water scarcity and inundation problems in urban areas (Gado & El-Agha, 2020).

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