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RESEARCH PAPER

Optimal Exploitation Strategies of Sustainable Utilization of Egypt's Fossil Groundwater Reserves

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Abstract

Groundwater-dependent areas in Egypt are being reclaimed as a result of the impending food crisis. Thus, the national project for land reclamation aims to turn vast tracts of desert land into productive agricultural land. Even while this kind of rural development is desperately needed, relying solely on fossil groundwater sources is a dangerous course of action. Therefore, it is crucial to use these groundwater resources quite carefully. Selecting a safe pumping schedule to prevent aquifer depletion and/or seawater intrusion is just one of the goals. However, using groundwater simulation models based on optimal approaches would introduce exploitation plans that, at the same time, guarantee the aquifers' sufficiency for continued development and maximize the agricultural investment. Thus, a groundwater flow model was generated using the FEFLOW software to explore the Moghra aquifer's potential for extensive rural development. The maximum pumping regime that coincides with the regulation rule that was set by the MWRI for the next 100 years has been concluded. There is a potential for sustainable exploitation of this water resource to irrigate a total area of 85,715 acres (34,687 ha). The resulting drawdown is expected to reach 95.4 m. Furthermore, a few mitigating techniques are suggested as efficient ways to stop or impede the saltwater intrusion, such as the installation of subterranean barriers and brackish water scavenger wells. Without a doubt, the intended findings would serve as the foundation for wise local water management choices that might strike a balance between the socioeconomic welfare of our nation and environmental preservation. The outcomes of the project can be used by decision making and stakeholder to achieve sustainable water resources management in the new lands for reclamation projects in the northwestern of Nile Delta, Egypt.

Keywords: Sustainable Utilization; Moghra Aquifer; Nubian Sandstone Aquifer; Seawater intrusion; Agricultural development.

1. Introduction

1.1 Research Background

In Egypt, rural development is essential to addressing the country's rising food demands, which will only get worse due to the country's rapidly expanding population. Thus, the main goal of Egypt's decision-makers is to move toward horizontal expansion in the vast desert in order to achieve food self-sufficiency and relieve the overcrowding along the Nile River by building new urban communities surrounding newly developed agricultural zones [1]. The official strategic plan 2030 featured a massive new cultivation project that aims to increase Egypt's inhabited area from 6% to

10%, extend its agricultural fields by 20%, and reestablish Egypt as a significant agricultural state [2]. The initiative was seen as a crucial step toward Egypt's future, where the government is prepared to boost GDP development, create new job opportunities, enhance the economy, and attain crop self-sufficiency [3]. Raise the water deficit [4], groundwater reserves will inevitably need to be used [5]. Egypt's water budget has previously been supplemented by shallow aquifers of the Nile delta aquifer [6]. Furthermore, there were a few community settlements and land reclamation initiatives across the western Nile Delta fringe [7]. The over-pumping has caused a drastic drop in water heads, and between the fresh groundwater in the Nile Delta aquifer and the saltwater that has invaded from the Mediterranean Sea, there is a sizable dispersion zone [8]. In order to prevent saltwater intrusion, Armanuos and Negm, [9] recommended reducing the pumping discharges of all wells. On the other hand, almost untapped reservoirs can be found in the desert aquifers, such as the Moghra, Fissured Carbonate, and Nubian sandstone. These aquifers offer a good opportunity for the promoted growth of agribusiness, and the government plans to use groundwater to supply the new reclamation areas' water needs [10]. The project was launched at the end of 2015 and is expected to be carried out in three stages [2]. The project subphases have split into multiple plots across Egypt, the majority of which are found in the western desert where it is claimed that the Moghra and Nubian sandstone aquifers have higher capabilities [11]. In an effort to cut costs, the government has committed to using photovoltaic panels to power an electrical water pump through the use of a solar water pump system. Sprinkler and trickle irrigation have been used to guarantee the physical efficient use of groundwater [12]. The primary obstacle to this project is the non-renewability of the aquifer systems, which raises serious concerns about groundwater sustainability.

Although the project's designated aquifers have a great potential for stored water [13], [14], their lack of major recharge sources illustrates the traditional characteristics of arid zone hydrology [15]. Put differently, there will be no compensation for the extraction related to the proposed development. In this scenario, groundwater extraction causes a reduction in the groundwater storage volume, which in turn causes a drop in groundwater potentiometric (water) level. Due to mismanagement and a lack of resources that could support a sustainable groundwater supply, these groundwater reserves are therefore in danger of depleting and deteriorating [16]. Nonetheless, there is ample opportunity to employ this resource, given that its utilization is guided by the principles of reason and discernment [17]. Consequently, it is critical to establish withdrawal regulations or discharging limitations in order to prevent overexploitation, which has detrimental effects on the surrounding area and interconnected ecosystems. For such aquifers with insufficient replenishment capacity, the safe yield concept outflow equals inflow is therefore inappropriate [18]. It is necessary to establish a specific management standard for every water-bearing formation that strikes a balance between the advantages of groundwater extraction and its drawbacks [19]. Given that the drawdown rate in the developing regions is less than one meter annually, the government of Egypt, prepared by the Ministry of Water Resources and Irrigation (MWRI), first designated a pumping plan to adopt the sustainable management [20]. Despite its significance, this limit is insufficient for all pumping fields because they differ significantly in their genesis and morphology. Consequently, it is necessary to specify the outcomes and financial return under this constraint.

1.2 Related work

The scientific community has started investigating and evaluating these groundwater facies' potential in order to facilitate their prudent use. A three dimensional or quasi-three-dimensional finite element or finite difference groundwater flow model was typically developed and validated, and it was then run under realistic scenarios of variations by testing the boundary conditions influenced by land use, groundwater recharge rate, evapotranspiration rate, and pumping rate. This allowed for the assessment of trade-offs among various scenarios for the pumping of water, as well as the diagnosis of the drivers of aquifer depletion and changes in water quality. Researchers [21], [22], [23] thoroughly investigate the six areas (Toshka, Farafra Oasis, Dakhla Oasis, Bahariya Oasis, West Minya, and East Owainat) where the new reclamation project is being carried out (or included in the upcoming two subphases). Large cones of depression are developing around the groundwater extraction areas as a result of the Nubian sandstone aquifer's fast growing water pumping, according to produced conceptual models. Most of the time, a very lengthy timeline that shows a significant amount of groundwater stored in the aquifer has been concluded, throughout which over-abstraction and adverse side impacts occur. Consequently, there should be a separate standardization and evaluation of the Nubian groundwater sustainability concept and criteria. On the other hand, the coordinated investment north of the Qattara depression, which is dependent on the Moghra aquifer, was constrained by the ensuing decline in the potentiometric heads [24], [25]. Furthermore, the ongoing pumping is making the case for seawater intrusion more compelling, as evidenced by researcher 2021 study. However, the government is encouraged to expand the reclamation areas to the south and east of the Qattara depression due to the area's high capability and appropriateness for agricultural uses, which are measured by various biophysical and socio-economic factors and soil suitability [23], [26]. The government launched two million-acre national agriculture projects, "New Delta" and "Mostkbal Masr," at the beginning of the current year, 2021 [27]. This put further strain on the Moghra and Fissured Carbonate aquifers to meet the demands for irrigation. As a result, it is becoming more important than ever to highlight the difficulties and important role that unrenewable groundwater management of these aquifers plays—problems that shouldn't be disregarded in favor of an integrated strategy.

According to similar earlier research, a recurrent worry is the lack of data needed to create reliable groundwater models; as a result, they would not be accepted as instruments for managing aquifers. Most of the time, the domains of the models were arbitrary defined as confined or unconfined single-layer systems. The existence of various aquifer systems has not been taken into account in these investigations. It is imperative to take into account all aquifers while modeling since there is interaction between the various formations during pumping. Moreover, the outputs of the models are more complex and ambiguous due to the groundwater intense wells number that are not spatially spread over larger areas. Therefore, the prior research was limited to a single pumping plot and did not take into consideration the interconnected implications of neighboring fields. Hence, a regional modeling of the complete development plots is required.

Lately, the use of mathematical models has greatly increased scientists' capacity to forecast these kinds of intricate aquifers under extremely intense stress [28]. Here, a comprehensive study will be conducted to develop novel management strategies that maintain the aquifers' capacity to store water and control the rate at which seawater intrusion migrates domestically under concurrent exploitation. These regulations will encompass not just pumping rates but also determining the best times and places to implement them [29].

According to researchers [30], [31], [32], and others, combining the simulation model with an optimization approach would produce more practical and resilient outcomes that would allow for the simultaneous achievement of conflicting objectives. We'll also talk about and assess a variety of groundwater management strategies. The economic water needs for the projects of these agribusinesses, which are related to Crop Net Return per unit volume of pumped water, will be explored in order to gain a better understanding of the behavior of irrigators on farm-level adaptation strategies.

1.3 Research Objective

The goal is to create an optimal exploitation plan that is spread spatially, maintains the aquifer's sustained yield capacity, meets current and future water demands, and protects the aquifer systems while taking both quantity and quality into account. More particular still:

i. Using Geographic Information System-based multicriteria decision analysis (GIS-MCDA), to investigate the study area potentials and the representation of a suitable map for the cultivation development projects and related activities (e.g., landfill sites). A decision-making process will be started to quantify each site's suitability for the acquisition of a new rural community or landfill site. A number of pertinent, disparate, and pertinent criteria will be taken into consideration when determining the suitability (e.g., geographical and biophysical characteristics and water accessibility and quality).

ii. To measure model uncertainty and get a thoughtful of the current state of the aquifer system through the use of a numerical model (the FEFLOW Model) that accounts for groundwater level, flow pattern, and water balance. This would be the first attempt, as far as we are aware, to address the uncertainties around the parameters of this aquifer (i.e., recharge, hydraulic conductivity, and distribution of unregistered wells).

iii. To ascertain future water requirements and potential aquifer exploitation policies while taking anthropogenic-induced consequences into account.

iv. The verified flow model will next be put through fictitious scenarios to see how terrible groundwater regimes will ultimately get as a result of improper or careless pumping.

v. To look into the effects that acceptable groundwater extraction plans would have on the hydrodynamics of the aquifer and its water quality in light of saltwater intrusion under various climate change scenarios.

vi. The increased freshwater pumping would hasten the encroachment of seawater and have unfavorable effects on freshwater availability. An alternate mitigation strategy should be considered and assessed in order to create a stagnant interface, reestablish the dynamic equilibrium between fresh groundwater and the saltwater, and improve the aquifer's groundwater quality without interfering with the socioeconomic operations in the pumping fields. In order to do this, brackish water from the dispersion zone must be pumped for a predetermined amount of time at varying discharge rates. The pumped water can then be utilized for irrigation of plants or crops with a high salt tolerance or for desalination.

vii. To create the best pumping plans possible, taking into account the well field locations and the aquifer's extraction rate. In order to accomplish development goals in a sustainable manner, targeted output is the most practical groundwater management method. The best pumping approach in terms of reliability would be examined in terms of uncertainty.

viii. To talk about groundwater management techniques and agricultural adaptation strategies to deal with the problems of rising salinity and establishing water usage guidelines.

ix. To provide an online application for groundwater flow in aquifer systems to support decision-making. As a groundwater decision support tool, integrating groundwater flow model simulation using an interface integrated into a web browser is, in fact, an entirely new technique.

2. Study Area

Egypt's agriculture industry will face a significant problem in providing food for its expanding population given the anticipated deficit in the country's water budget [33]. As a result, it is recommended to implement a development project and numerous megaprojects in order to enhance the cultivated area approximately 4 million acres spread over Egypt's drylands (Figure 1). Beginning in 2016, the Egyptian government implemented agricultural policies encompassing 1.5 million acres [5]. The project's goal is to expand horizontally into the newly discovered desert areas. As a result, they mostly (90%) rely on the nonrenewable groundwater of the Nubian Sandstone Aquifer and the Moghra aquifer in the western deserts of Egypt. In the Egyptian desert, groundwater extraction was viewed as a potential source of additional conventional water [2]. Pumped groundwater is currently widely used in newly farmed areas, mostly for irrigation but also for home purposes. It is anticipated that the amount of groundwater pumped would rise annually. If groundwater became the only source of freshwater on these lands, the dynamics of aquifers would be altered, particularly in light of the limited water availability, which is a crucial development barrier. The management of Egypt's two aquifer systems—the Moghra and Nubian sandstone aquifers, for example—is more complicated due to their scarcity or non-renewability. Nonetheless, there is still a great deal of space for the application of rationality-based concepts with this resource.

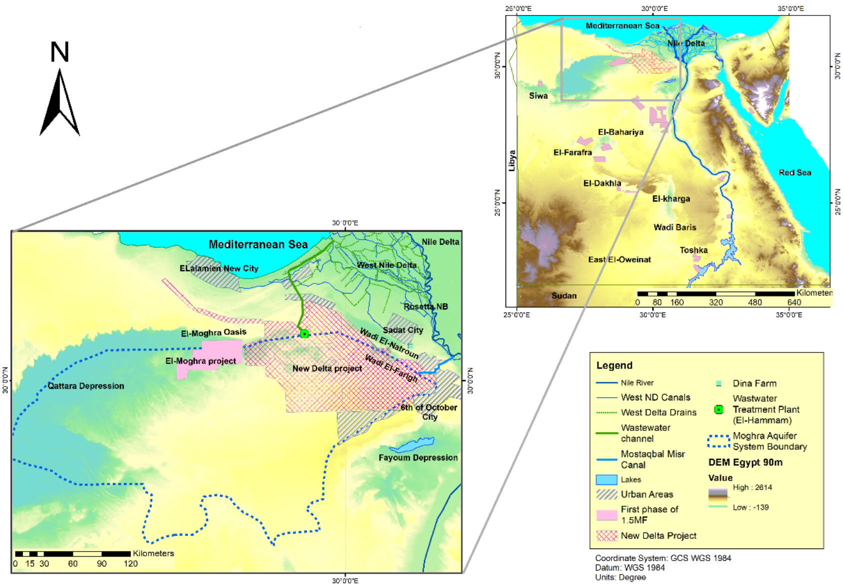

Figure 1: *a) Location map of the 1.5 M acres project, b) Location of the New Delta project and the Moghra aquifer.*

The 50,000 km^2 Moghra desert region near the western tip of the Nile Delta is covered by the Moghra groundwater aquifer system, a mixture of fossil water, in addition to the renewable water, located in the northern part of the Western Desert [34]. According to researchers [25], the majority of the aquifer's sediments are coarse sand and fluviatile and fluvio-marine gravel from the Miocene, with intercalations of siltstone and clay. The aquifer's base is level with the earth in the north and west, while it falls from a depth of up to 900 meters in the center [35]. The aquifer receives minimal replenishment from seepage from the Nile Delta aquifer, upward leakage from the adjacent Miocene limestone aquifer and Nubian Sandstone Aquifer System, and a small amount from the annual rainfall by the infiltration process. The primary sources of aquifer discharge include lateral seepage into carbonate formations and evaporation from small depressions, such as in the eastern area by Wadi El-Natroun and Qattara depression in the western area [14], [36]. The salinity of the aquifer water varies, with a narrow wedge near the Nile delta having a slightly brackish 1,000 ppm salinity and the other portion of the aquifer having a saline up to 12,000 ppm salinity [37]. One of the regions chosen for the nationwide mega project for the land reclamation, which got underway in late 2015, is the Moghra desert. To support continued agricultural and fish breeding operations, about 200 Mm^3 of water will be abstracted each year [38]. Table 1 presents the previous research conducted in the Moghra aquifer, western deserts of Egypt.

Table 1: *The previous research conducted in the Moghra aquifer, western deserts of Egypt.*

Study	Location	Title
[14]	El-Moghra Aquifer	Groundwater Potentials and Characteristics of El-Moghra Aquifer in the Vicinity of Qattara Depression.
[11]	Egypt's 1.5 million Feddan Project	Groundwater Exploitation in Mega Projects: Egypt's 1.5 million Feddan Project
[28]	–	A Review of Groundwater Management Models with a Focus on IoT-Based Systems
[29]	Qatar	Approaches to achieve sustainable use and management of groundwater resources in Qatar: A review.
[18]	India	Causes and implications of groundwater depletion in India: A review.
[22]	Western Desert, Egypt	Maximizing the management of groundwater resources in the Paris'Abu Bayan reclaimed area, Western Desert, Egypt.
[39]	Qattara Depression, Western Desert, Egypt	Groundwater origin and management in Moghra Oasis and its vicinities, Qattara Depression, Western Desert, Egypt.
[26]	El-Moghra Depression, Egypt	Classification and Land Capability of Some Soils at El-Moghra Depression, Egypt.
[21]	Farafra Oasis, Western Desert of Egypt	Sustainable Agricultural Groundwater Management for New Reclaimed Areas in Farafra Oasis, Western Desert of Egypt.
[40]	El-Moghra aquifer, Egypt	Sustainable groundwater management in ElMoghra Aquifer.
[16]	–	The issue of groundwater salinization in coastal areas of the mediterranean region: A review.
[24]	El-Moghra aquifer, Egypt	Management Scenarios of Moghra Aquifer, Western Desert.
[25]	El-Moghra aquifer, Egypt	Sustainable groundwater management in arid regions considering climate change impacts in Moghra region, Egypt.
[38]	El-Moghra Oasis, Egypt	Multi criteria analysis for groundwater management using solar energy in Moghra Oasis, Egypt.
[13]	Western Desert, Egypt	Development of Groundwater Flow Model for Water Resources Management in the Development Areas of the Western Desert, Egypt
[23]	Toshka Area, Western Desert, Egypt.	Groundwater Assessment for Agricultural Irrigation in Toshka Area, Western Desert, Egypt.
[32]	–	Adaptive management in groundwater planning and development: A review of theory and applications.

3. Methodology

A five-step process would be used to formulate such integrated management and optimally exploiting methods, as illustrated in Figure 2. It covers the process of investigating the capabilities of the research area, creating a groundwater model, formulating model optimization plans, and creating a web application. The following paragraphs presented the five-step process in the adopted methodology.

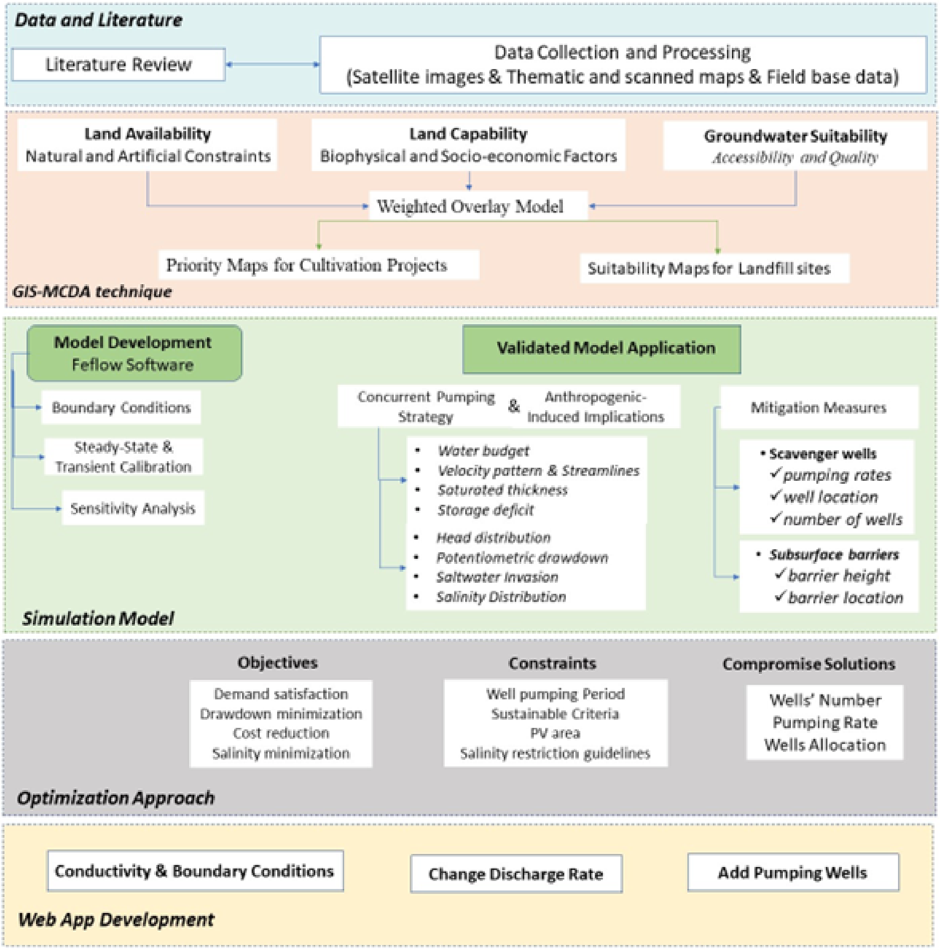

Figure 2: *An overview of the adopted research methodology in the current research.*

3.1 *Survey*

In order to better understand simulation – optimization approaches, how they function for optimization, what tools and techniques are available, how they are used globally, and how they might aid in achieving study objectives, a review of the current literature will first be conducted. An illustrative survey conducted throughout the Moghra aquifer to examine the fresh groundwater resources management at farms, institutional and collective aspects of management, mapping of stakeholders, institutional arrangements, analysis of beneficiaries, cropping patterns, land tenure, labor market, marketing, drainage, and salinization of soil. To know a deeper thoughtful of the Moghra aquifer, data and information on the location, geology, stereography, topography, climate, land use, soil, pumping wells, natural springs, and water abstraction, among other aspects of the aquifer systems, will be gathered from a variety of sources, including field trips and borehole logs. Table 2 shows the data collection sources for the required hydrological parameters. In addition, a survey of the literature on groundwater model uncertainty assessment will be implemented to provide a wide-ranging considerate of the sources, varieties, and methods of assessing groundwater model uncertainty.

Table 2: *The information of the collected dataset of the current study.*

Parameter	Data source
Aquifer thickness	(1) fifty-four groundwater exploration wells were excavated by the Egyptian Ministry of Water Resources and Irrigation (MWRI) to locate groundwater supplies in the Western Desert of Egypt. (2) forty-two deep boreholes were drilled by the national oil companies to explore for fossil fuels in the Western Desert.
Hydrogeological data, including depth to the water table, wells logs	Gathered from the Egyptian Countryside Development Company (ECDC) (https://elreefelmasry. com).
Topography	Digital Elevation Model (DEM) processed from the Shuttle Radar Topography Mission (SRTM)
Water quality data	Collected through the field trip and analyzed in an internationally accredited laboratory, Scientific Research Center and Measurements (SRCM), belonging to Tanta University, Egypt
Landsat images	Using land sat 8 from united State Geological Survey (USGS) website
Soil texture	FAO Soil Portal (https://www. fao.org/soils-portal/data-hub/soil-maps-and-databases/en/)

3.2 Multicriteria Analysis and Groundwater Modelling

Planning is necessary to assist in identifying the best locations for reclamation land development and mapping the best locations for landfills. This study will use a Geographic Information System (GIS) to support MCDA, which will make it easier to zone possible rural villages within the Moghra aquifer. The analytical hierarchy process (AHP) method will be utilized to determine the relative relevance of data related to topographical information, insolation intensity, area accessibility, groundwater investigation, and soil characterization. AHP entails assigning weights to the different parameters considered in the analysis. Weights reflect each criterion's relative importance to the others and consider the degree of compensation for all factors. The method shows promise for producing priority maps that will help planners for upcoming land development projects across Egypt and for creating models that forecast the appropriateness of the land for various agricultural products and crop rotations. Using the FEFLOW software, which is particularly well-suited for challenges involving complicated model architecture and is capable of handling saturated and unsaturated conditions, develop and verify an integrated numerical model approach. The program is capable of simulating a region this size and obtaining a finer resolution inside the pumping field. The database will be set up to assist in creating appropriate FEFLOW input data sets.

3.3 Groundwater Simulation Model for Sustainable Aquifer Management

The aquifer systems' groundwater simulation model, which has been built, will be used as an imitating model. To evaluate the hydro-geological conditions of the aquifer, the model will first replicate the current scenario (e.g., water budget, head distribution, velocity pattern, pre-developed saturation thickness of aquifer etc.). After then, the model will be modified for use in more research. Additionally, it will be used to simulate fictitious future water consumption scenarios in order to explore any potential repercussions and explain how overexploitation in the aquifer under study would result in a decline in water quality. In order to ensure sustainable development, it will be used to:

i) assess the decline in the water table caused by groundwater extraction;

ii) investigate how the pumping rates actions in the Moghra aquifer system affect the seawater intrusion in light of climate change and the ensuing the sea level rise; and

iii) assess alternatives to decisions made within the framework of Integrated Water Resources Management (IWRM).

iv) Modify the next actions to meet the long-term sustainable goals.

To get a sense of the accuracy of the model outputs, the Monte Carlo approach will be used to evaluate the model's uncertainty for parameters including well distribution, hydraulic conductivity, and aquifer recharge.

3.4 Optimizing Groundwater Management Strategies

Due to a phenomenon known as seawater intrusion, excessive groundwater use for agricultural purposes, particularly in such coastal areas, would raise the salinity of the groundwater. Because of the region's need for development and rising water demand, cutting back on pumping is probably not an option. It has been demonstrated that a strategically planned brackish water abstraction well, situated at a reasonable distance from the shore, is a cost-effective mitigating approach. The main objectives of the current project are to investigate the ideal pumping rates, well locations, and groundwater abstraction number wells by using the FEFLOW verified model. The effects of varying pumping rates and the separation between a well's position and the coast will be examined, and the optimal course of action will be described. The general quality of the groundwater would have improved, and one of the planned desalination plants in the Moghra aquifer may use the pumped brackish water as a source. The maximum pumping rate is 1.3 Mm^3/day in the Moghra aquifer through 1000 wells which is sufficient to irrigate about 92,850 acres (about 37,575 ha) with an average water duty of 14 m3/acres/day. However, climate change would carry out substantial pressure on the aquifer to encounter the expected rise in crop consumptive water usage. To evade the damage of a portion of the reclaimed parts in the upcoming, a time-increasing abstraction rate must be practical. Consequently, the established model was employed to examine the combined effect of SLR and the rise in crop-consumptive water usage. A time series representing a linear rise by 0.5 m in sea level during the upcoming 100 years was assigned for the northern boundary condition along the Mediterranean Sea.

3.5 Groundwater Management Planning

An approach utilizing a multi-objective optimization algorithm is necessary for long-term planning of groundwater utilization. The optimization model will be integrated with the simulation model, and the goal function and model constraints will be used to determine the best pumping techniques. Together with the underlying hydrogeological process, the topography, land use, water usage, and aquifer characteristics will aid in the formulation of management methods that include optimization constraints and goal functions. Reliability, or the likelihood that the generated optimal pumping techniques would succeed after being put into practice, will be used to assess the uncertainty of the strategies. The best model will be subjected to Monte Carlo simulation while taking unknown model parameters into account. Every Monte Carlo simulation realization's attainment of the model constraints will be evaluated, and that realization's success or failure will be determined. For that ideal pumping method, reliability will be assessed based on the number of simulations completed and their success rate.

3.6 Web-Based Development

In order to support decision-making, a web-based application for the groundwater flow model will be created. This can show how the changes in pumping or aquifer features affect groundwater head distribution and the water budget. Groundwater model modifications and simulations, as well as output extraction, will be carried out using the web server, GIS data server, and GIS data SQL (Structured Query Language).

4. Result and Discussion

4.1 Sustainable management of groundwater

Egypt's Vision 2030 lays forth a plan for achieving sustainable development that protects natural resources, makes sure they are used and invested wisely, and upholds the rights of future generations. The restricted water resources of Egypt country are under increasing pressure from current development plans to meet the growing demands of all sectors of the economy. As a result, Egypt's reliance on groundwater has become essential to achieving the ambitious government plans for the megaprojects for the reclamation of Egypt's deserts [41]. Hence, it is critical to focus research goals on developing the necessary sustainable management plans for both present and future use in order to prevent overexploitation, which has detrimental effects on all surrounding areas and interconnected ecosystems. Researchers [41] review the findings and approaches of research on groundwater use and management in Egypt's deserts that has been done over the past thirty years. It is explained how relying on simulation modeling software to plan and manage Egypt's groundwater reserves has drawbacks. It is demonstrated that the majority of groundwater studies conducted in Egypt tested abstraction scenarios for various simulation periods by simulating local areas in the groundwater aquifer systems with inadequately defined the boundary conditions and scant historical data. This impacted modeling accuracy and led to disparities between simulation results and aquifer parameter estimations. An open access monitoring network that represents the regional aquifers is required in order to propose trustworthy sustainable plans for the development of groundwater resources and recommendations for future conservation strategies [41]. It is imperative to conduct additional research based on in-depth field trips to display the environmental, the economic, and the social circumstances, identify barriers, and draw lessons specific to desert regions. The necessity of developing a sensible plan for the long-term strategies for the sustainable exploitation and restoration (quantity and chemical quality) of the nonrenewable Egyptian aquifer systems was also brought to light by this review. Additionally, a suitable exit strategy for desert communities in the event that the aquifers seriously depleted needed to be developed [41].

4.2 Groundwater monitoring (GRACE model)

Gravity Recovery and Climate Experiment (GRACE) mission enables a novel consistent approach to deriving aquifers' storage changes. Using the monthly release 06 (RL06) GRACE solutions from three processing centers (CSR, GFZ, and JPL), researchers [42] estimated changes in terrestrial water storage (TWS) from the year of 2003 to the year of 2021. Variations in the soil moisture (SM) and groundwater storage (GWS) are the primary causes of these changes. Variations in the groundwater storage (GWS) have been calculated by deducting the content of the soil water anomaly that the GLDAS-NOAH hydrological model produced. The linear least square method was implemented to govern the secular trends in the TWS and its two major components, the GWS and the SM. Mann-Kendall's tau, a non-parametric technique, was then used to verify the trend significance. According to the GWS alterations, as shown in Figure 3, there is a noticeable rate of loss in all aquifers. The average rate of groundwater level depletion over the Nile delta aquifer was assessed to be 0.32±0.03 cm/year, but the rate over the Sinai Peninsula was estimated to be 0.64±0.03 cm/year. From 32 Mm^3/year during the period of 2003-2009 to 262 Mm^3/year for the period of 2015-2021, the Moghra aquifer's loss has multiplied. This is a result of massive water pumping operations that are used to expose aquifers and irrigate recently planted areas [42]. The conclusions drawn from the aquifers' storage variation offer an invaluable resource for comprehending groundwater dynamics, which can greatly enhance Egypt's capacity for both short- and long-term groundwater planning. But in order to evaluate uncertainty and raise the technique's level of proficiency, the validation of the data obtained from GRACE model compared with the in situ well measurements, when available, is necessary [42].

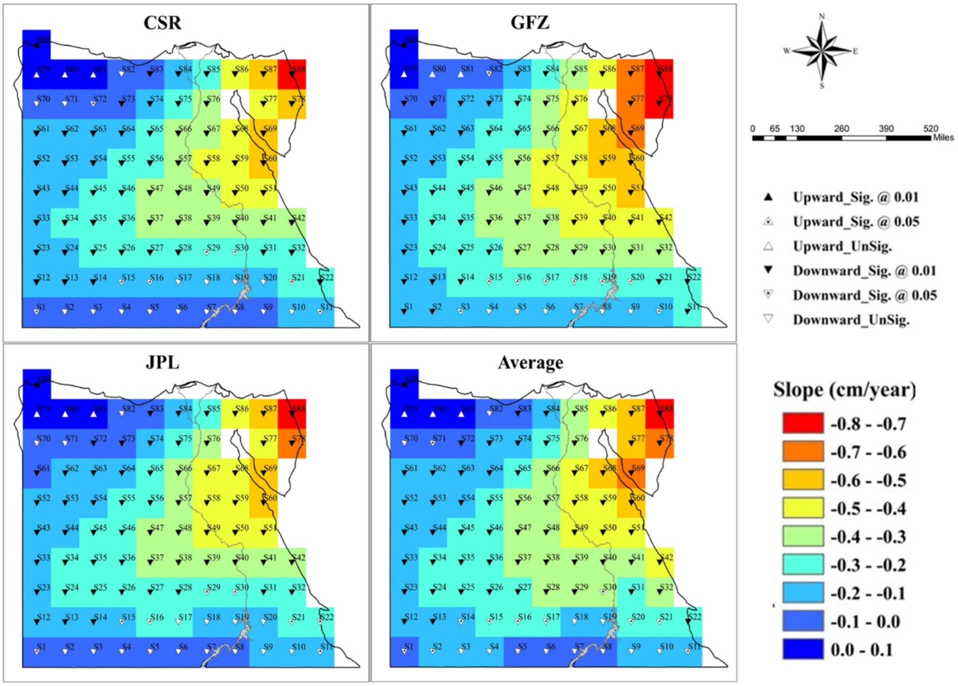

Figure 3: *Trend map of groundwater storage (GWS) in Egypt derived from GRACE data collected from 2003 to 2021.*

The time series of yearly variations in the GWS of the Moghra groundwater aquifer, obtained from GRACE - SM data. The aquifer's storage has been steadily declining since 2015, the year it was made ready for groundwater irrigation, according to the data. A modest declining trend of (0.04 ± 0.03) cm /year has been seen during the years 2003 to 2009. The aquifer was essentially regarded as unexplored during this time [36]. Evapotranspiration (ET) is the cause of the decline in aquifer storage during the first study period [25]. The subsequent dated from the year 2008 to 2015 sees a 0.17 ± 0.03 cm/year reduction in aquifer storage. According to researchers [14], some shallow wells that only partially penetrate the aquifer are the cause of the rise in storage loss. For the first two periods, there was a 32 Mm^3/year and a 135 Mm^3/year decrease in aquifer storage. In the third phase (2014–2015), the loss increased to 262 Mm^3/year. As part of the mega national project for land reclamation, a sizable portion of the western desert is irrigated with this enormous amount of piped water, as shown in Figure 4.

4.3 Groundwater management

Mainly in the arid regions and the semi-arid areas with limited rainfall and limited surface freshwater bodies, coastal aquifers are a vital supply of freshwater for the entire world. Groundwater supplies are becoming more and more important for the growth and urbanization of coastal zones in

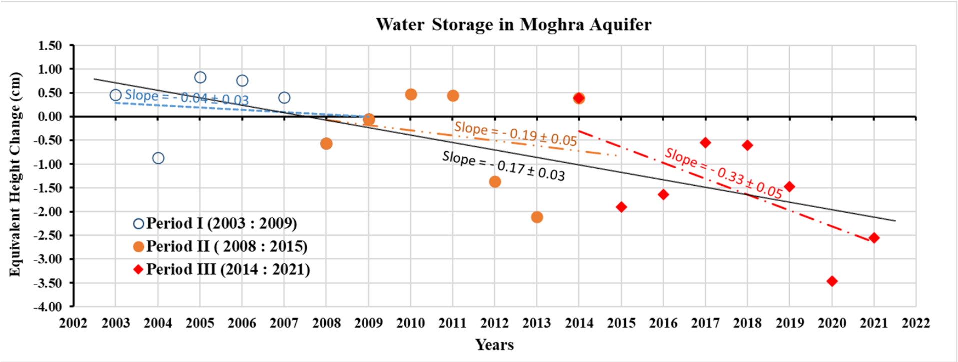

Figure 4: *Changes in groundwater storage in the Moghra aquifer estimated from GRACE data.*

dry and semi-arid countries, [43]. Researchers [43] offer helpful details on previous research on groundwater sensitivity to contamination, groundwater flow modeling, saltwater intrusion modeling, sustainable groundwater management studies, and Nile Delta aquifer monitoring and data availability. Researchers [43] provides an overview of the numerous approaches put forth by academics. The investigations primarily looked at how the global waterway (GW) is becoming more salinized in various deltas.

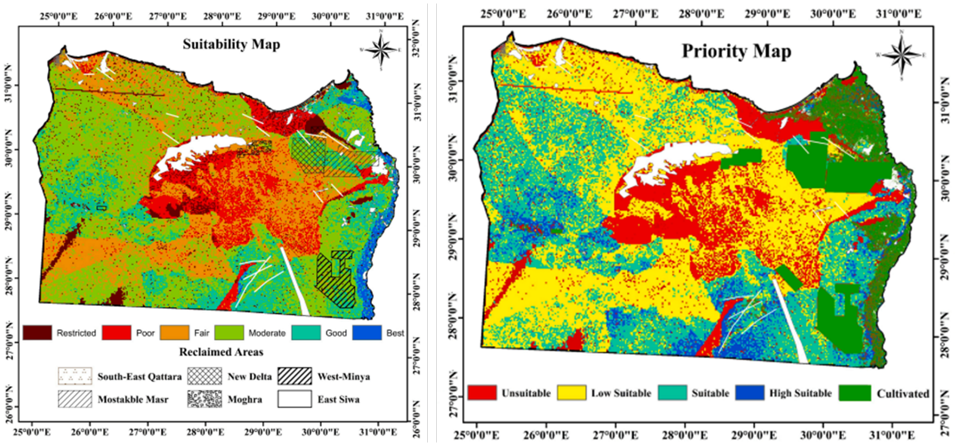

Figure 5: *Suitability map (a) and Priority map (b) for allocating new cultivation projects.*

4.4 Multicriteria decision analysis

To help identify the most advantageous locations for such reclamation land development, planning activities are unavoidable. Researchers [44] used a Geographic Information System (GIS) to enable a MCDA that will help with zoning for future rural villages in Northwestern Egypt. Along with the slope and aspect angle maps, which were raster files, the area solar radiation map was also modeled using data from the Shuttle Radar Topography Mission (SRTM). It was discovered that 20 million hectares of uncultivated land, divided into Best, Good, and Moderate classifications, were suited for this type of agriculture. Every farm that is now in use and every area that is being recovered is located inside the high, agriculturally acceptable pixels, confirming the created model's validity. The method that was chosen looks promising in terms of yielding priority maps that would help planners for upcoming land development projects across Egypt. Robust methods for determining if a piece of land is suitable for a certain crop should be developed [44]. Figure 5 presents the suitability map and priority map for allocating the new cultivation projects in the northwestern area of the Nile Delta.

4.5 Groundwater quality index

The Moghra Aquifer is regarded as nonrenewable, and the continual, extraordinary overdraft has caused a significant decline. Pumping should be limited in order to preserve a drawdown threshold and prevent paleowater depletion. The projected development's water responsibility may be satisfied by the aquifer's potential for storing water. However, saltwater intrusion (SWI) would make the aquifer's ability to deliver groundwater suited for agriculture much more stressed [45]. In order to evaluate the aquifer's inherent vulnerability to SWI, a thorough methodology that combined a GIS-based implemented model integrated with the hydro-chemical indicators was used in this instance. Based on six hydrogeological criteria, GALDIT is a mapping index that serves as a representative tool for assessing the susceptibility of SWI. Sensitivity analysis was used to evaluate each criterion's relative importance [45]. According to GALDIT, one-fifth of the development area was categorized as highly vulnerable, and two-thirds as moderately vulnerable, as shown in Figure 6. Its dependability was validated by the intensity of the link between the TDS readings and the GALDIT-based vulnerability maps. However, when it came to zoning the most sensitive plots, the updated GALDIT model performed better. It has increased the field area of the wells in the high and medium vulnerability categories by 13.38% and 5.17%, respectively. 94 out of 101 samples were identified by the piper diagram as having the (Na+ - K+ - Cl- - SO42-) ion association, which denotes the presence of SWI. The bulk of samples (91%) were identified as Na-Cl chemical water types by the HFE diagram [45].

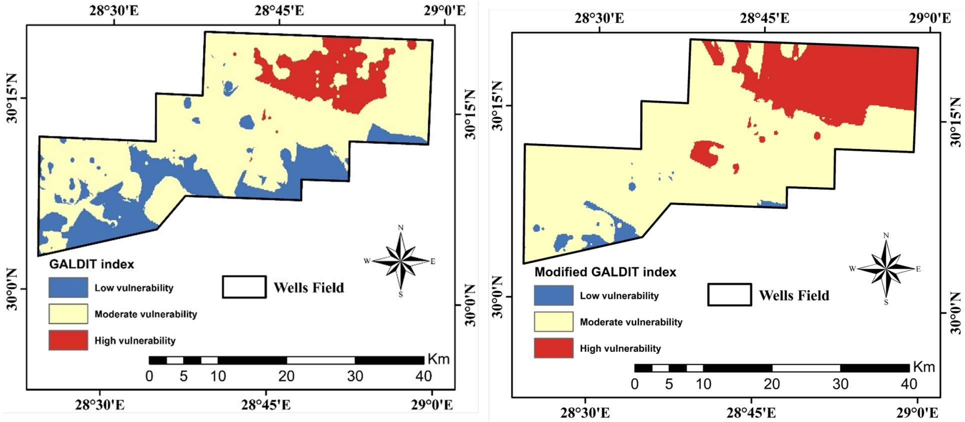

Figure 6: *Vulnerability map: (a) Original GALDIT vulnerability index map, (b) Modified GALDIT vulnerability index.*

4.6 Landfall site selection

A massive development project is underway in an effort to create new integrated towns in the wide desert in order to alleviate the overcrowding near the Nile River. Researchers [46] found appropriate locations in the western desert's new development plots for solid waste disposal. Seven significant criteria were incorporated into the site selection model: land use, slope, elevation, stream network, distance from road accessibility, groundwater (GW), and soil permeability. MCDA integrated with and GIS were used to assess and analyze the criteria. 94.25% (20980.5 km^2) of the research area has inappropriate landfill conditions, according to the results of the criterion overlay using the BL approach, while 5.75% (1280 km^2) of the research region has adequate landfill locations. As seen in Figure 7, it indicates that the research region's north and south-west were the best locations for landfills [46].

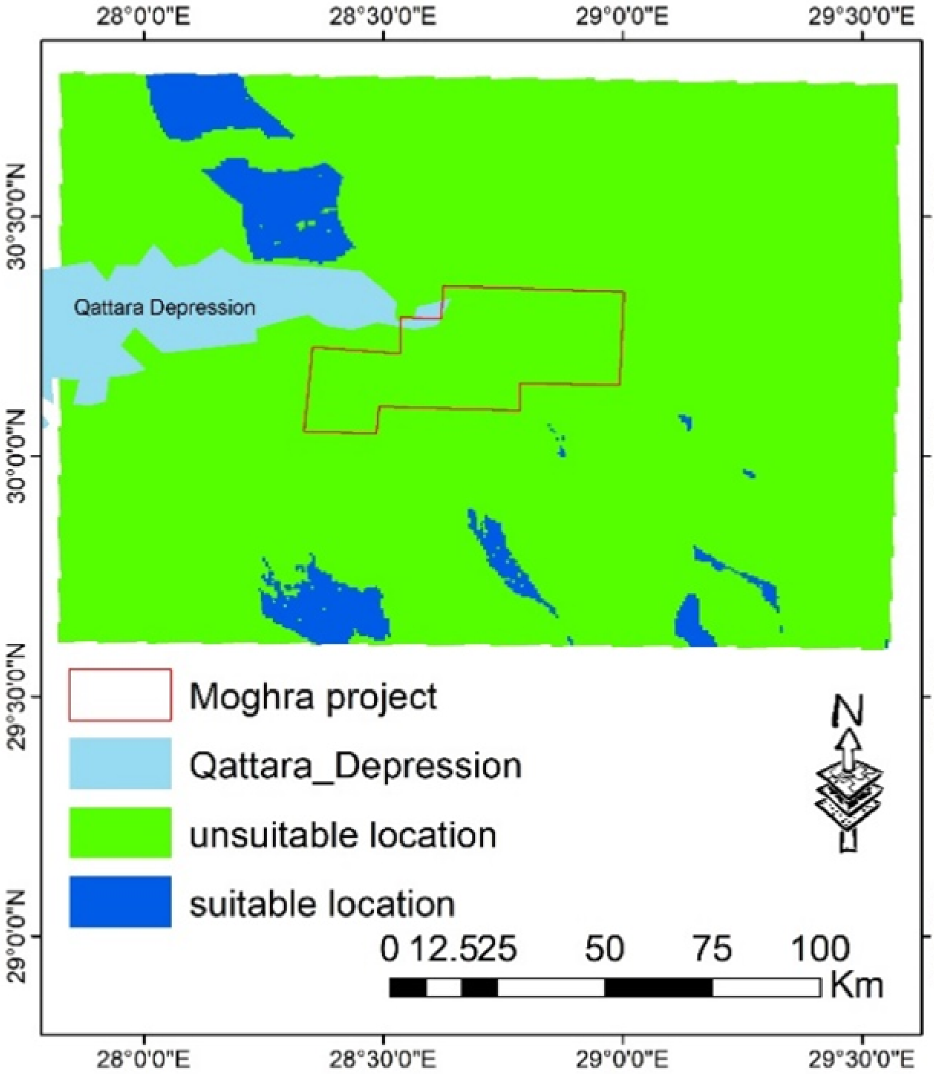

Figure 7: *Landfill map using Boolean logic.*

4.7 Groundwater modeling

Researchers [17] implemented a three dimensional finite element groundwater flow model, or FEFLOW, to investigate the possibilities of the Moghra aquifer, where a sizable rural population is being built. The generated model's calibration was done using the actual water levels. Groundwater storage based on GRACE was integrated into the model's tuning process. During a 100-year test period, eight different abstraction rates from 1000 wells varying from 800 to 1500 m3/day/well were tested numerically. The resulting maximum drawdown values varied from 59 to 112 m, which corresponds to approximately 20-40% of the thickness of the saturated depth of the Moghra aquifer.

The effects of a slow rise in sea level and a rise in the crop consumptive water consumption on climate change were examined. The worst-case scenario of climate change (i.e., RCP 85) was used to assess the expected increase in crop water requirements. To water the cultivated area without reducing it, a commensurate temporally increasing abstraction rate was set, [17]. The MWRI's regulating rule for the next 100 years, which corresponds with the maximum pumping regime, was completed. This water resource has the potential to be used sustainably to irrigate 85,715 acres (34687 hectares) in total. As shown in Figure 8, it is anticipated that the next drawdown will be 95.4 m [17]. Decision-makers can use the established model and its outputs to define sustainable management techniques in a useful way. To assess the extent to which the groundwater production wells would introduce seawater into the groundwater Moghra aquifer system, it is recommended that the model be upgraded [17].

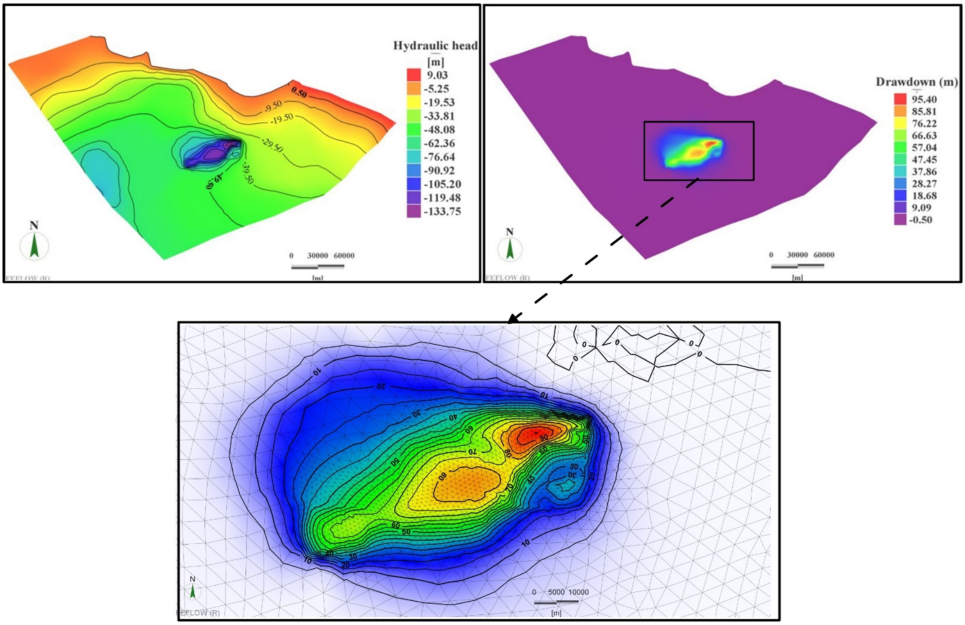

Figure 8: *Simulated hydraulic heads (Left) and drawdowns (Right) after 100 years of applying the recommended development regime under the combined effects of climate change.*

5. Conclusion

In the semi-arid areas and the arid areas all over the world, water and food limitation issues have heightened over the last twenty years. In Egypt, a mega land reclamation project is now employed under the framework of moving towards horizontal expansion in the barren lands distanced from the Nile River. It is mainly depending on the groundwater for development and fulfilling various requirement of water. The main objective of this project is to present an overview of a research project on the sustainable management of fresh groundwater resources in new reclaimed area, Moghra region, Egypt, through the following research steps. The Moghra aquifer storage is estimated by application of the GRACE- based approach. MCDM with the integration of GIS was implemented to explore the Western Desert's potential for cultivation development projects (about 1.5 million ha, representing 7.2% of the undeveloped area, were found to be highly suitable for future expansion of agribusiness activities), evaluate the groundwater vulnerability to pollution (one-fifth of the development area was categorized as highly vulnerable), appropriate landfill sites selection (5.75% of the research region has adequate landfill locations), and assessing the aquifer vulnerability to seawater intrusion. FEFLOW was conducted to build three-dimensional model of the Moghra aquifer. The built groundwater model was tested for various scenarios of climate change including sea level rise and different schemes of abstraction rates. Different mitigation measures for seawater intrusion will be checked for the coastal development area. The outcomes of the project can be used by decision making and stakeholder to achieve sustainable water resources management in the new reclamation lands in northwestern of Nile Delta, Egypt.

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