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ORIGINAL ARTICLE

Enhanced groundwater availability through rainwater harvesting and managed aquifer recharge in arid regions

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Abstract

Climate change in desert areas and semi-arid watersheds may offer a promising solution for the water scarcity problem that Bedouins and local inhabitants face. This study investigated the integrated water resources management in arid and semi-arid regions using rainwater harvesting in combination with the managed aquifer recharge (RWH-MAR) technique. The study also used recharge wells and storage dams to achieve the sustainability of groundwater supplies in the context of climate change and management of the flow to the Gulf of Suez. Therefore, different return periods of 10, 25, 50, and 100 years were considered for the annual flood volume resulting from those watersheds. Moreover, hydrologic modeling was carried out for the El Qaa plain area, South Sinai, Egypt, using the Watershed Modeling System (WMS) and the groundwater modeling of SEAWAT code. Our findings show that for different scenarios of climate change based on return periods of 10, 25, 50, and 100 years, the aquifer potentiality reached 24.3 MCM (million cubic meters) per year, 28.8 MCM, 36.7 MCM, and 49.4 MCM compared to 21.7 MCM at 2014 with storage of groundwater ranges 11.8%, 32.1%, 69%, and 127.4%, respectively. These findings have significant implications for the system of RWH-MAR and groundwater sustainability in El Qaa Plain, South Sinai. The RWH-MAR proved to be an effective approach that can be applied in different water-stressed and arid regions to support freshwater resources for sustainable future development and food security, as well as protect communities from extreme flash flood events.

Keywords El Qaa plain · Climate change · Flash floods · Rainwater harvesting · Recharge wells · Storage dams

Introduction

Limited water resources are increasingly strained by growing demands for agriculture, drinking water, and industry, particularly in areas already coping with drought. This situation is further exacerbated by the impacts of climate change, which disrupts traditional watershed patterns and reduces water availability (Abd-Elaty et al., 2022a; Ibrahim et al. 2023). Flash floods (FF) are critical natural disasters worldwide, influencing people's lives, the economy, and infrastructure, especially in arid or semi-arid zones; watershed management and planning are essential for reducing flood damage (Akib Jabed et al. 2020; Jonkman 2005; Prama et al. 2020; Abd-Elaty et al. 2023). Also, FF is one of the most strenuous challenges we face in the twenty-first century (Jha et al. 2012). The Intergovernmental Panel on Climate Change (IPCC, 2014) published that climate change exacerbates many regions due to increasing the recurrence and magnitude of FF (Sharma and Ravindranath 2019; Abd-Elaty et al. 2024).

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Rainwater harvesting and artificial recharge are among the most promising alternatives for supplying freshwater in the face of increasing water scarcity and escalating demand (Misra 2019). The best management of FF promotes fresh groundwater storage, preventing FF hazards and keeping the soil from drifting. Also, infiltration through the basin streams from the rainwater harvesting systems is the major source of artificial groundwater recharge and management for the present and future demands during the dry season (Mostafa et al. 2019; Zhang et al. 2020). Artificial recharge is a source and technique for sustainable groundwater resources in arid and semi-arid areas. The potential artificial recharge by flooding harvesting is better for mitigating the water shortage from over-pumping (Ibn Ali et al. 2017). Also, the aquifer storage and recovery (ASR) uses the same pumping wells to recharge the aquifers in wet and low-demand seasons from the precipitation and abstraction in dry seasons. This methodology has been widely used as an alternative solution for surface water storage in aquifers to reduce the construction cost of these structures and storage in surface reservoirs (Jeong et al. 2018). ASR technique stores the additional water through deep injection in coastal aquifers. The stored water is then recovered using the same recharge wells to provide the community's water supply during the next dry or high-demand years (Alqahtani et al. 2021). Also, ASR describes intentional banking and treatment of water in aquifers (Dillon 2005).

The interactions between fresh groundwater and surface water are effective for water demand. This sharing between the two systems can increase efficiency and improve water shortages and environmental conditions. Increasing the abstraction well rates due to overpopulation and climate change are expanding the water demands and the abstraction from the aquifers. Moreover, fresh groundwater resources provide about 31% of the world's drinking water (Bear et al. 1999; El Shinawi et al. 2022). Eldeeb (2019) conducted a field study to investigate the interaction between surface water and groundwater due to the construction of New Dairut Group Regulators in Assuit, Egypt. The field measurements showed that a confined aquifer is underlying the study area, and the two systems have a hydraulic connection. Abd-Elaty and Zelenakova (2022b) used different techniques and strategies for coastal deep and shallow aquifers' freshwater sustainability in high-aridity regions using the hydraulic method. The results showed that the hydraulic method is positive and affects the mitigation of saline water intrusion in shallow and deep coastal aquifers.

The flood's runoff losses are compound infiltration and evaporation. The infiltration is estimated by the Horton Equation, Green-Ampt model, Phi index method, initial and constant loss, and the Soil Conservation Service (SCS) curve number (CN) method (SCS 1972). Smemoe et al. (2004) tested the CN and the Green-Ampt methods. The study indicated that the Green-Ampt method performed better than the CN method. Chahinian et al. (2005) compared the performance and consistency of four infiltration models. The results indicated that Morel-Seytoux's model was better than the Philip, Horton, and SCS methods. Also, the consistency of Horton's method was better than Philip's. The flood runoff estimation uses different methods, including kinematic wave, nonlinear kinematic wave routing, synthetic unit hydrographs, EPA SWMM/nonlinear reservoir, 2D diffuse wave, Wallingford, large catchment, SPRINT, and SWMM. Sherman (1932) introduced the concept of unit hydrograph (UH), which is the runoff for unit depth of excess rainfall based on a uniform-intensity storm.

Morad (2000) used the HEC-1 code to estimate the potential of water resources in the Wadi Sudr basin, Sinai, Egypt. The results showed that the storm events and the generated runoff hydrographs were deduced to construct the interrelationship of the basin hydrologic characteristics. Al-Salamah et al. (2011) estimated its excessive use's impact on Saq aquifer depletion in Buraydah in the Kingdom of Saudi Arabia. The results concluded that the pumping from the aquifer would result in significant cones of depression if the existing excessive pumping rates prevailed. It has been recommended that the management scheme be adopted to protect groundwater resources. Elewa and Qaddah (2011) integrated enhanced Thematic Mapper Plus (ETM +) images, GIS, a watershed modeling system (WMS), and weighted spatial probability modeling (WSPM) to investigate the groundwater potential in Sinai, Egypt. The study showed that Sinai has moderate groundwater potentiality for about 33,120 km^2, representing 52% of its total area. Ahmed (2012) applied gravity and magnetic data over the El Qaa plain by using 381 ground gravity stations and 800 lines of aeromagnetic data to assess the hydro-geologic settings, aquifer structures extension, geometry, and water storage in El Qaa plain. Aboelkhair et al. (2020) studied the integration of geospatial techniques for mapping groundwater potentialities in El Qaa Plain, Sinai, Egypt; the results showed that remote sensing data along with geospatial techniques could provide a powerful tool for groundwater probabilities in arid lands. They thus can be applied in regions with similar conditions, such as the Middle East countries. Yousif and Hussien (2020) increased the opportunities for groundwater potential in Sharm El Sheikh, South Sinai, Egypt. They mitigated the flooding risk, enhancing the environment under arid conditions through groundwater recharge. Elbarbary et al. (2021) applied the HEC-HMS package to forecast the runoff in Wadi El-Meleiha, Sinai, Egypt. The study showed that accuracy would be improved by accounting for the excess rainfall for the spatial and temporal variation in predicting direct runoff hydrographs. The current study uses the Watershed Modeling System (WMS) and variable density groundwater model using SEAWAT. It investigates the impact of rainwater harvesting recharge by flash flooding for sustainable groundwater supplies in the desert of El Qaa plain, Sinai, Egypt, due to climate changes for different recurrence intervals of 10, 25, 50, and 100 years. The study proposed rainwater harvesting using recharge wells and storage dams for the basin water resources management and decreasing the flow to the Gulf of Suez.

This study assesses the potential of using rainwater harvesting in combination with managed aquifer recharge (RWH-MAR) in the desert of El Qaa Plain, Sinai, Egypt. This technique holds promise for enhancing freshwater supplies and securing water resources for the sustainable development of arid coastal regions, especially in drought seasons. Also, the RWH-MAR prevents rainwater from evaporating or flowing into the sea unused, maximizing water capture and protecting the communities from the risk of flood hazards.

Materials and Method

Hydraulic aquifer recharge

This study uses two techniques for rainwater harvesting: artificial recharge using recharge wells and *natural* recharge using a storage dam. The method is required to increase the aquifer freshwater storage to overcome over-pumping problems and climate change in arid and semi-arid regions.

Artificial recharge consists of a positive or pressure barrier; the coastal aquifers are artificially recharged to increase fresh groundwater's hydrostatic force and increase the piezometric heads to overcome the saltwater intrusion. Generally, this method minimizes flash flood risk, increases fresh groundwater heads and storage, relieves drawdown by over-pumping, improves water quality, and suppresses the saline water body (Yomoto and Islam 1992; Tanim and Goharian 2021;). Ghazaw (2009) investigated how damages from runoff can be reduced and how extra runoff can be used to recharge. The study results will be helpful in runoff control, mitigation of damages from runoff, and appropriate storage and recharge of runoff in various areas of Saudi Arabia.

Natural recharge this technique feeds the aquifers with excess surface water by constructing dams and weirs to manage the runoff flowing directly to the sea and flood protection (Fig. 1a). This methodology aims to help infiltrate the retained water in the soil to increase the volume of fresh groundwater storage and help in SWI management. However, this solution is better for unconfined aquifers requiring high top layer permeability; depending on top layer properties, the aquifer recharging process could take a long time. The construction and maintenance costs of required structures for this method are very high. This method is unsuitable for confined and deep aquifers (Abbas et al. 2020).

The recharge well is used for low flood volume with a 1 m diameter and 100 m depth, while the storage dams are used for large flooding volume. The well recharge is suitable and operational in certain hydrogeological settings, for the aquifers do not get the natural recharge because of the confining layers of low permeability (Hernandez 2014); the recharge well is presented in Fig. 1b. The recharge dams for the groundwater occur through the base of the pond and downwards to the underlying aquifer. The water in a reservoir is released over several days/weeks so it can gradually infiltrate through the riverbed downstream. The most effective recharge dams have silt removal mechanisms to allow the release of silt to maintain the infiltration rate (Standen et al. 2020) (Fig. 1c).

The recharge type was selected based on flood volume and aquifer type. Using a storage recharge dam with high permeability in an unconfined aquifer is good. In contrast, the recharge wells are good in semi-confined and confined aquifers for low permeability. In this study area, the Wadi El-Aawag watershed has high permeability, and the aquifer is unconfined, so the surface runoff will easily infiltrate groundwater.

Wadi El-Aawag Watershed

Wadi El-Aawag watershed, one of the largest basins in southwestern Sinai, flows into the Gulf of Suez drainage system. It locates between latitudes 28° 15′, 28° 45′N and longitudes 33° 20′, 34° 00′ E. It occupies an area of about 1960 km^2, locally named Sahl El Qaa (Fig. 2). This area was selected as a promising zone in the Sinai for future development and tourism activities, increasing the number of inhabitants and expanding land use (El-Rawy et al. 2020). This area of the Wadi El-Aawag watershed is bounded in the North and East South by mountainous hard rocks while in the South by the Red Seas and Gulf of Suez at the west. The main water supply for the city of El Tor depends on the surface and groundwater recharge by the Wadi El-Aawag Watershed.

The watershed's trunk channel generally extends about 58 km from the north and northeast to southwest. Topographic elevations varied between 1 m and 2566 m (Fig. 3a). This plan is a promising area for future land use planning and agricultural activities for shoreline extension to about 180 km with suitable soils of low, sandy, and gravelly surface, which differ significantly from the adjacent eastern high mountainous hard rocks of South Sinai.

The watershed varied in slope degree from a gentle slope (<6) to a very steep slope in the eastern part of the watershed (67.7 m/m) (Fig. 3b). The watershed is covered by four land use /land cover units. The built area class is represented mainly by the area close to El Tur City at the

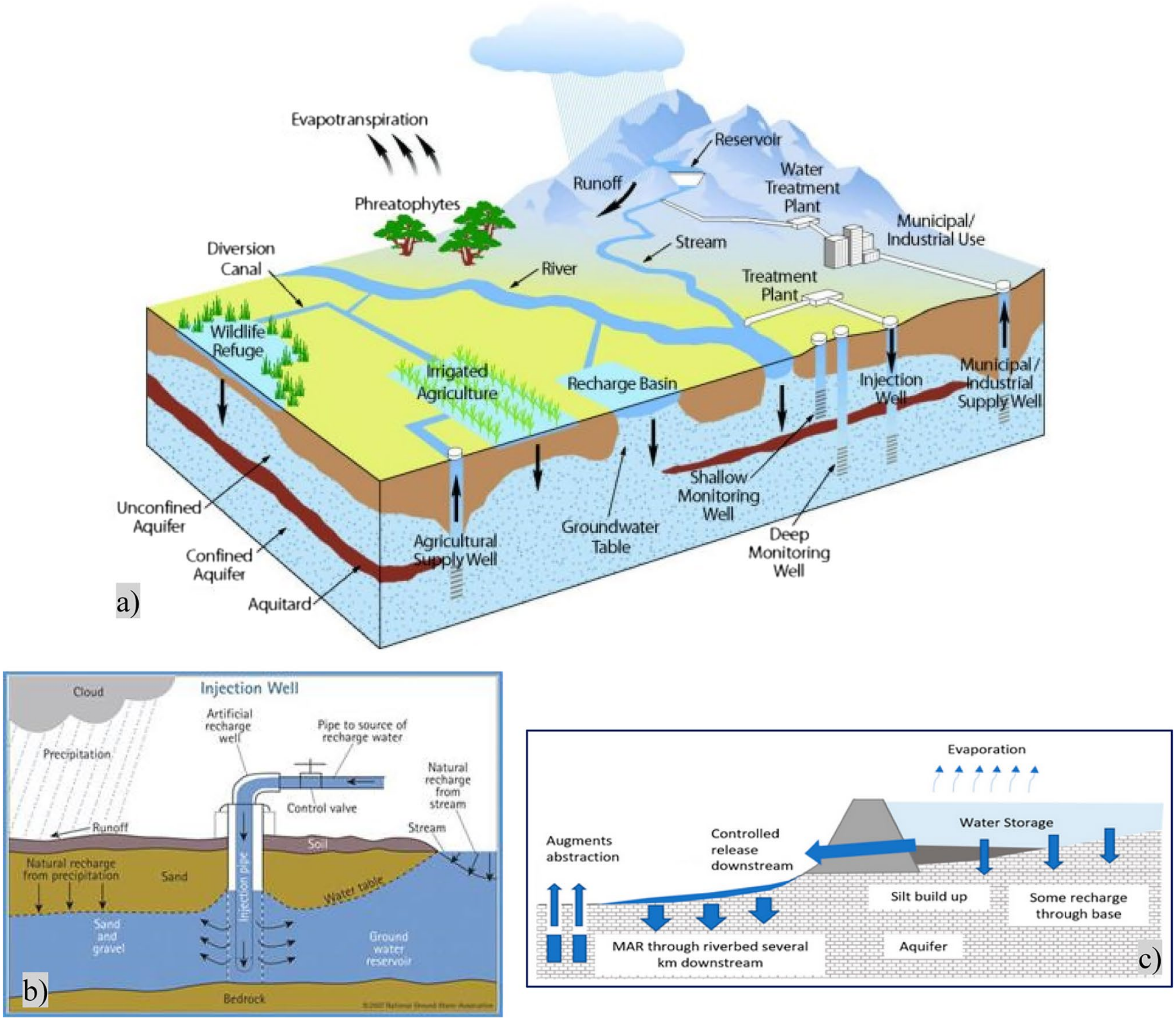

Fig. 1 Managed aquifer recharge for **a** Integration between surface and groundwater after INOWAS (2023), **b** recharge wells (Veeranna and Jeet 2020), and **c** storage dams (Standen et al. 2020)

Wadi outlet. Cultivated lands are occupied by the downstream area (El Qaa Plain area), which is represented by many agricultural farms irrigated by the water extracted from the El Qaa Plain aquifer. The bare lands occupy most of the watershed, while rangelands are observed on the eastern and western sides. The land use and land cover (LULC) is significant for mapping the variation in soil types and anthropogenic activities in the plain area, which is critical for runoff infiltration (Fig. 3c). The figure shows the five classes of LULC: basement rocks, old alluvial deposits, recent and wadi deposits, sedimentary rocks, urban & roads, and vegetation (Yousif et al. 2020).

Hydrological model

The hydrological frequency analysis was carried out using the HYFRAN-Plus software V2.1 in the Wadi El-Aawag watershed to estimate the return periods (RP). Also, the precipitation in El Tur and Saint Catherine stations from 1981 to 2022, where the minimum, average, maximum, and total annual rainfall was 0.38 mm, 7.18 mm, and 30.01 mm for El Tur station, while the Saint Catherine station reached 0.41 mm, 33.73 mm, and 8.92 mm, respectively, as presented in Fig. 4.

The recurrence intervals were estimated for different distributions. Log-Pearson type III developed a good fit for the

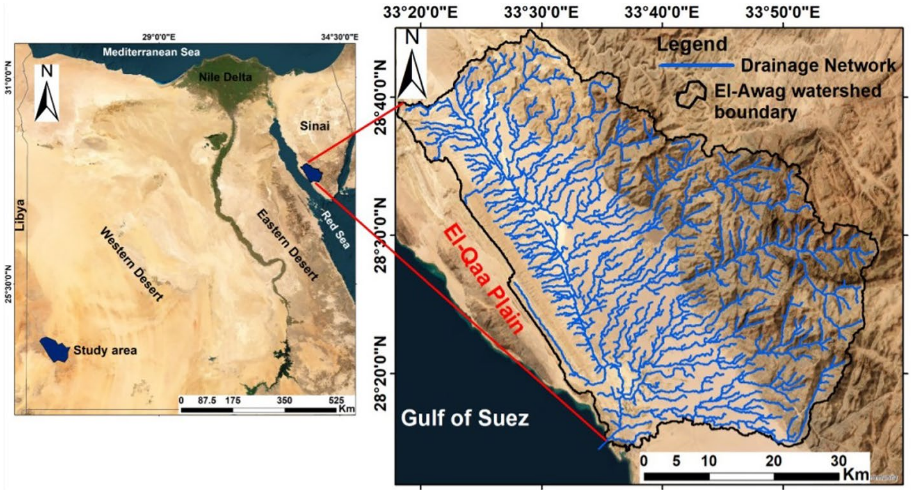

Fig. 2 Study site location and drainage network of W. Elawag watershed

precipitation in El Tur stations. The predicted precipitation values reached 18.8 mm, 30.1 mm, 40.7 mm, and 53.4 mm for different return periods (RP) of 10, 25, 50, and 100 years.

Wadi El-Aawag Watershed Geology and Hydrogeological setting

Wadi El-Aawag watershed geology predominantly comprises Precambrian and Cambrian rocks (Fig. 5). The Quaternary deposits are mainly from the El Qaa Plain, a coastal plain that is a promising aquifer for groundwater storage.

Wadi El-Aawag consists of twelve sub-watersheds from the north to South. The El Qaa Plain has a high mountainous range in the eastern part; these mountains play a vital role in the coastal plain development. Many drain of the watersheds plain (wadies) originated from these granitic mountainous massive and formed the Gulf of Suez drainage system in the study area. These wadies are buried within El Qaa Plain during the Quaternary times and become active during the rainy periods (Eltahan et al. 2021; Gaafar et al. 2018). These separate drainage systems are suitable for delivering mountain sediments to the El Qaa Plain and recharging groundwater during flooding. This plan attains the sixth order following the main geologic structures and rock contacts.

Figure 5a presents the El Qaa Quaternary aquifer system on the eastern coast of the Suez Gulf in the South of the study area. Also, it is bounded from the east by the high Precambrian crystalline basement rocks and from the west by the sedimentary carbonate rocks (Gabel Qabeliat). It is formed mainly of alluvial deposits and detrital materials detached from the surrounding basement rocks. It is characterized by high to moderate productivity. The Quaternary aquifer system in the El Qaa Plain is characterized by high storage capacity. It receives considerable amounts of recharge from the El-Aawag Watershed. This Quaternary aquifer in El Qaa Plain is the main source of fresh groundwater in South Sinai for El Tur and Sharm El Sheikh Cities. Lithologically, the aquifer consists of three layers, which are hydraulically connected. The aquifer lithological consists of sand, gravel, silt, and rock fragments detached from the basement rocks, varying between 700 m and 1000 m (Abbas et al. 2020), as shown in Fig. 5b.

El-Quad watershed modeling description

The Watershed Modeling System (WMS) is software for the El Qaa Plain to carry out hydrologic and hydraulic modeling of a watershed. The software modules include:

The terrain module uses digital elevation models (DEM) data for floodplain delineation and mapping. This stage was applied for morphometric analysis of watersheds using DEM with 90 m; the study area resolution was obtained from the SRTM (Shuttle Radar Topography Mission data). Also, the geological and topographic maps were used to understand the different unit distributions for land use and soil type in the study area.

Drainage module is used for drainage basins and streams. The drainage network extraction for El Qaa Plain was performed through its sub-modules using the TOpographic PArameteriZation program (TOPAZ) after the watershed was delineated and subdivided into sub-watersheds. The drainage basin's characteristics, including areas, slopes, and maximum flow distance, were estimated.

The hydrologic modeling module uses Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS) software to determine the rainfall-runoff relationships based on watershed characteristics by simulating the hydrological processes for basins and sub-basins to estimate the hydrographs for different watersheds. The HEC-1 can be used to develop the hydrological model by simulating a single watershed or a system of multiple hydrologically connected watersheds; it requires different

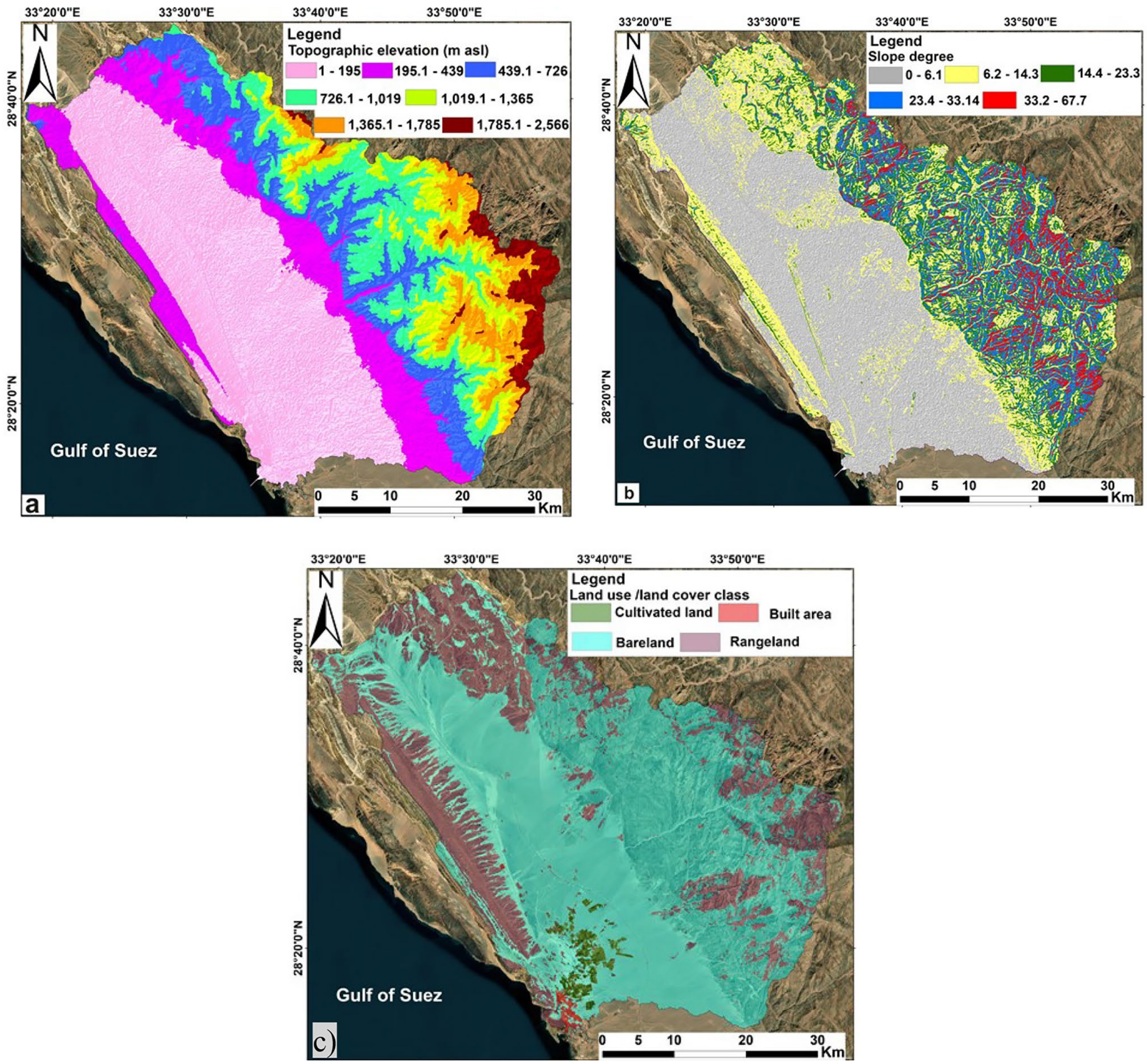

Fig. 3 Study area: **a** topographic elevations, **b** Slope degree, and **c** Land use / land cover map

datasets for DEM, precipitation values, soil type, and land use. The SCS curve number method is developed in the current simulation to estimate the losses. Also, the water quantities and inflow rate calculations were calculated using the SCS unit hydrograph approach. Furthermore, the hydraulic modeling module used the Hydrologic Engineering Center- River Analysis System (HEC-RAS) to design the streams and detention structures (El-Fakharany and Mansour 2021; Gülbaz et al. 2019). The mean annual rainfall of El Qaa Plain was used in performing the WMS 8.0© from the meteorological stations' El Tor using different recurrence intervals. Also, the losses of the SCS-CN method used 88, the hydrograph approach was applied using SCS, UH, and the hydrograph was estimated. The flood volumes in the current study area of El Qaa Plain reached 89,892 m^3 at an average annual rainfall of 17.1 mm in 2014, which was used to calibrate the groundwater model.

Figure 6a presents the stream order for the El Aawag watershed, which has the sixth order. Table 1 and Fig. 6b show the characteristics of the El Aawag watershed and its sub-basins for the basin area, slope, average overflow, length, perimeter, shape factor, sinuosity factor, average basin elevation, maximum flow distance and slope, and maximum stream length and slope.

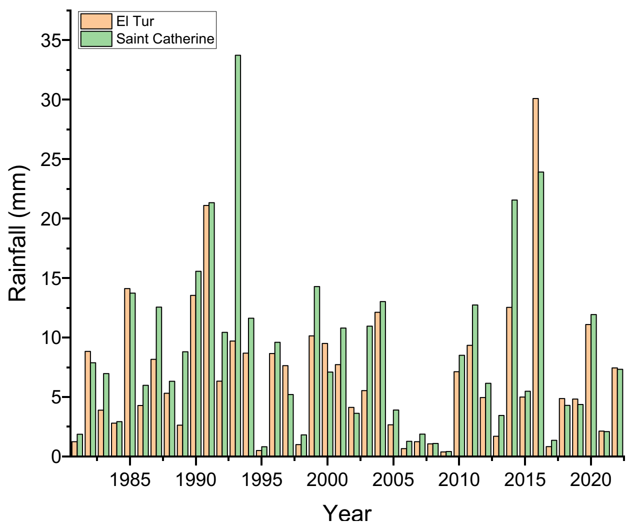

Fig. 4 Annual rainfall depths in the El Qaa aquifer

Surface runoff estimation

This method has Clark Unit Hydrograph, Snyder UH, Nash UH, and SCS UH. The watershed area was delineated using the SCS method as the following (USDA-TR55 1986; Gitika and Saikia 2014):

$$\mathrm{S} = (25400 - 254\mathrm{CN})/CN \tag{1}$$

$$\mathrm{Q} = (\mathrm{P} - 0.20\mathrm{S})/(P + 0.80S) \tag{2}$$

The concentration time, defined as the runoff time required to travel from the most distant point to the basin's outlet point, is used in flood assessment. Kirpich equation (Chow et al. 1988) is used to compute the time of concentration described as follows:

$$\mathrm{T_c} = \frac{0.00013\mathrm{L}^{0.77}}{\mathrm{S}^{0.385}} \tag{3}$$

where S = potential maximum retention (mm), CN = curve number, P = rainfall for different return periods (cm), Q = the depth of direct runoff (mm), T_c is the time of concentration in hours; L is the length of the overland flow (m); S is the average overland slope in (m/m).

El Qaa groundwater modeling description

El Qaa aquifer was simulated using SEAWAT code by variable density coupling. It is the modified MODFLOW (Langevin et al. 2003) and MT3DMS (Zheng and Wang 1999) into SEAWAT_V4 (Langevin 2009). The variable density groundwater flow equation is solved using the variable density flow (VDF) process developed by Guo and Langevin (2002) as the following:

$$\nabla\left[\rho\frac{\mu_o}{\mu}K_o\left(\nabla h_0 + \frac{\rho - \rho_o}{\rho_o}\nabla Z\right)\right] = \rho S_{S,0}\frac{\partial h_O}{\partial t} + \theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} - \rho_s' q_S' \tag{4}$$

where ρ: the density of saline water [kg m^{-3}]; μ_o: the dynamic viscosity of freshwater [kg m^{-1} s^{-1}]; μ: the dynamic viscosity of saline water [kg m^{-1} s^{-1}]; K_0: the hydraulic conductivity [m sec^{-1}]; h_0: the hydraulic head [m]; ρ_o: the fluid density [kg m^{-3}] at the reference concentration; $S_{s,0}$: the specific storage [m^{-1}], t: time [sec]; θ: is porosity [-]; C: the concentration [kg m^{-3}]; q'_s: the volumetric flow rate of sources and sinks per unit volume of aquifer [T^{-1}] with a density of ρs [kg m^{-3}].

The groundwater flow model is solved using the finite-differential method by dividing the system into a grid of cells. Each cell has a single node point where the groundwater heads are calculated (McDonard 1988).

Model design and geometry

The groundwater conceptual model was developed based on topography using DEM files, geology data, and hydrogeological studies. The Quaternary aquifer of El Qaa consists of gravel, sands, clays, and sandy clays. It is considered the main sediments composing the plain area (Sultan et al. 2009). The aquifer system is divided vertically into three hydrological units north of El Qaa Plain. The first aquifer is the upper unit by the lithological composition of gravels with a sand layer. It represents a limited area in the W. El-Aawag Watershed near El Tur City. Layer #2 is the middle unit by a soil of sand and gravel with clay lenses. It is considered the main groundwater unit with a 60 km length and 10 km width, occupying about 600 km^2 based on the hydrogeological maps of Sinai (JICA 1999). Its bottom is 20 m to over 100 m below sea level (masl). The deepest place is about 15 km northeast of El Tur City, representing the lower unit by sands and gravels with silt and clay. As previously discussed, these hydrological units are hydraulically connected (Fig. 3a).

The model has a rectangular dimension of 60,324 m in width and 65,380 m in length, representing an active aquifer dimension of 66 km (max. length) and 24 km (max. width). The El Qaa aquifer model includes many rows and columns, 200 and 200, respectively, using cell dimensions of 160,000 m^2.

Boundary conditions and hydraulic parameters

Figure 7a presents the boundary conditions for the El Qaa aquifer, which are essential for a flow model construction, reflecting the relationship between the studied aquifer

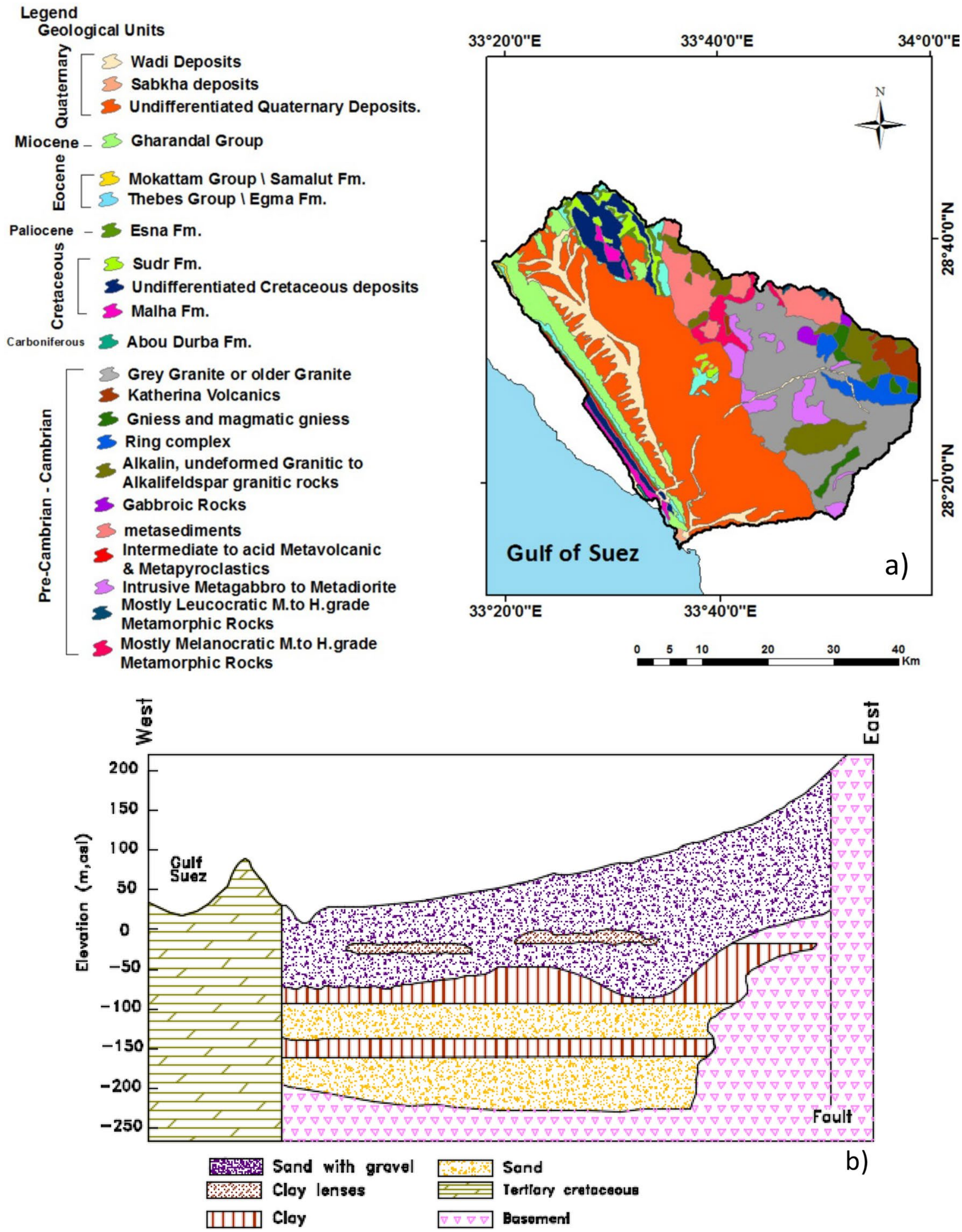

Fig. 5 The study area: **a** simplified geological map of W. El-Aawag Watershed after Conoco (1987) and **b** conceptual (schematic cross section of El Qaa Plain after JICA (1999)

system and the surrounding systems. This study's area for the Quaternary aquifer of El Qaa Plain is classified into the eastern boundary as a recharge boundary. It receives recharge from the runoff water. El-Aawag Watershed's constant head condition represents the western boundary by zero head for the Gulf of Suez. No flow boundary represents the study areas of no flow to the aquifer, which were assigned on the west side for the mountains of basement rocks (Table 2).

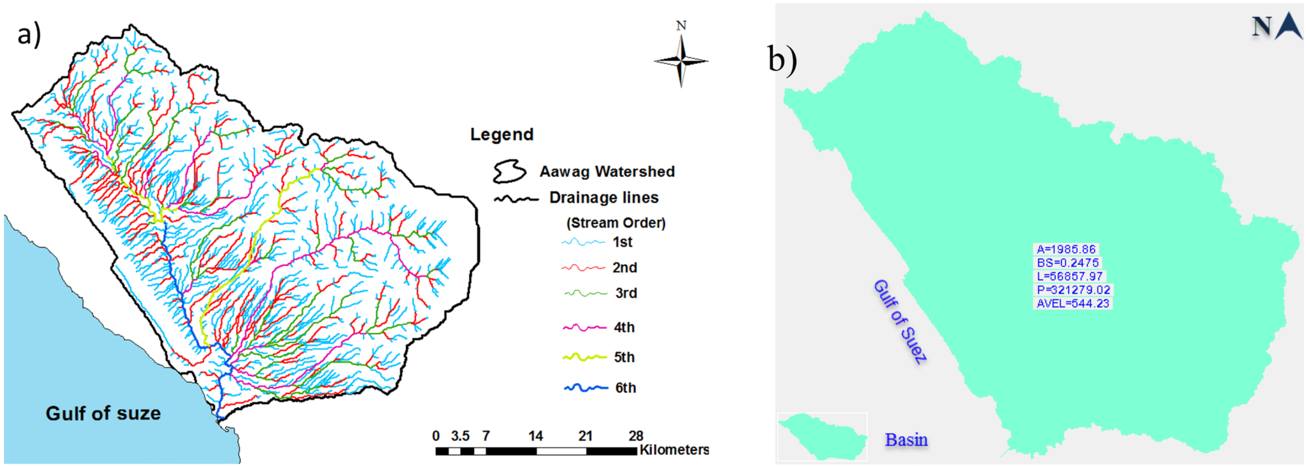

Fig. 6 The El Aawag watershed: **a** basin's stream order and **b** its characteristics and sub-basins

Table 1 Characteristics of El Aawag watershed

Parameter	Unit	Value
Basin Area	A (km^2)	1985.86
Basin Slope	BS (m/m)	0.2475
Av. Overflow Dist	AOFD (m)	637.30
Basin Length	L (m)	56,857.97
Basin Perimeter	P (m)	321,297.02
Shape Factor	Shape (mi2/mi2)	1.63
Sinuosity Factor (MSL/L)	Sin	1.42
Basin Av. Elevation	AVEL. (m)	544.23
Max. Flow Distance	MFD (m)	82,351.42
Max. Flow Slope	MFS (mm^{-1})	0.0154
Max. Stream Length	MSL (m)	80,551.82
Max. Stream Slope	MSS (m/)	0.0116

The aquifer hydraulic parameters were based on the data collected from JICA (1999), the Water Resource Research Institute (WRRI), and other studies using pumping tests for the production wells. The hydraulic conductivity of the eastern margin reached about 50 m day^{-1} with sandy gravel and gravelly sand. At the same time, the coastal area consists mainly of limestone and has a lower hydraulic conductivity of about 5 m day^{-1}. The transmissivity varies between 106 m^2 day^{-1} and 2150 m^2 day^{-1}, with an average of 768 m^2 day^{-1}. The specific storage ranges between 0.33–6.11, with an average value of 2.64. The effective porosity is 43.1% to Sultan et al. (2009). The three aquifers have hydraulic gradients of about 0.00395, 0.006, and 0.000775 (Elbeih 2015).

Abstraction and recharge

The abstraction rates for production wells in the El Qaa aquifer increase with increasing agricultural activities. All these wells depend basically on the El Qaa Quaternary aquifer system. Wells' yield ranges between 20 m^3 hr^{-1}and 15 m^3 hr^{-1}, with an average value of 56.7 m^3 hr^{-1}. The groundwater abstraction from the El Qaa aquifer reached 8550 m^3 day^{-1}, 13040 m^3 day^{-1}, 10270 m^3 day^{-1}, and 8820 m^3 day^{-1} in the years 1971, 1984, 1987, 1990, and 1992, respectively (El-Rawy et al. 2020), and reached 17,000 m^3 day^{-1}, 18,000 m^3 day^{-1} in 2004 and 2008, respectively (Elbeih 2015; Masoud 2015). The amount of recharge from the watersheds on the eastern side is about 5.9×10^6 m^3 year^{-1} (Masoud 2015). The recharge was estimated to be 16,840 m^3 day^{-1} in the year 2000.

Also, the aquifer received a modern annual recharge of 39×10^6 m^3 year^{-1} in 2020. The renewable water in the El Qaa aquifer ranges between 20 and 70% of the total aquifer storage (Yousif and Hussien 2020). The current model used an abstraction rate of 23,136 m^3 day^{-1} in 2014, while the recharge was 59,507 m^3 day^{-1}, as presented in Fig. 7b.

Model scenarios

The groundwater model was simulated for the seven scenarios for RP by 10, 25, 50, and 100 years applying Rainwater Harvesting combination with the Managed Aquifer Recharge (RWH-MAR) technique for the El Qaa plan using WMS software and the groundwater flow model of SEAWAT for rainfall events of 18.80 mm, 30.10 mm, 40.70 mm, and 53.40 mm respectively.

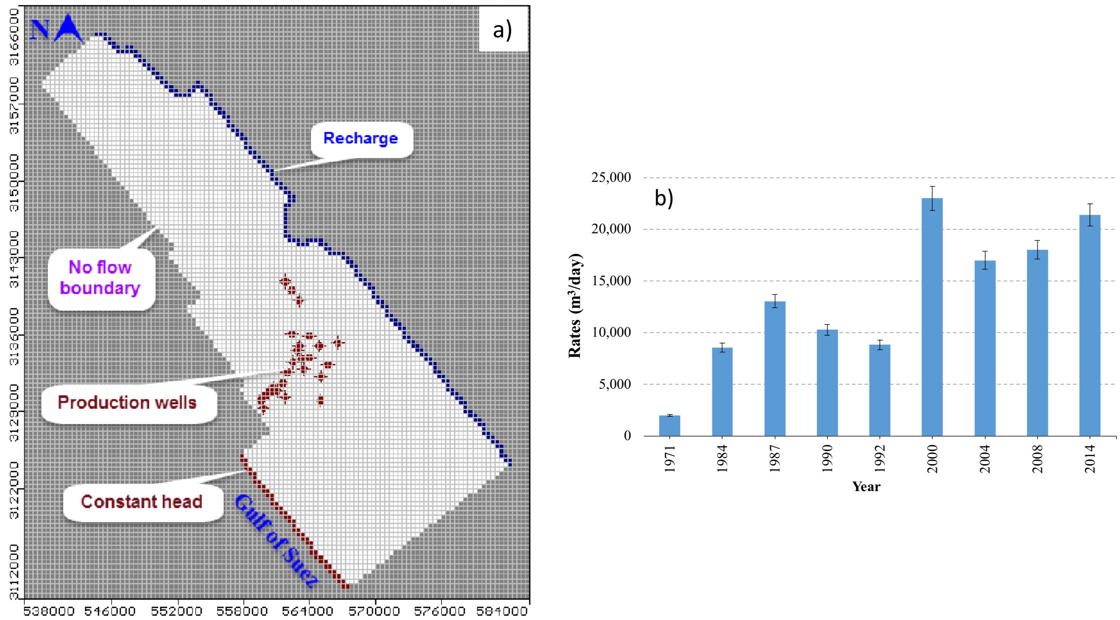

Fig. 7 El Qaa Quaternary aquifer: **a** model geometry and boundary conditions and **b** average groundwater extraction through the years

Table 2 Calibrated hydraulic parameters and boundary conditions used in the El Qaa groundwater model

Hydraulic Parameters	Symbol	Top layer	Unit
Horizontal hydraulic conductivity	(K_h)	1–60	m day^{-1}
Vertical hydraulic conductivity	(K_v)	0.10 to 6	m day^{-1}
Transmissivity	(T)	106–2150	m^2 day^{-1}
Specific storage	(S_s)	0.33	m^{-1}
Specific yield	(S_y)	0.10	–
Effective porosity	(n_e)	41.30	%
Flow to the aquifer	R	500	mm $year^{-1}$
Abstraction rates	A	8.44×10^6	m^3 $year^{-1}$

Results

The analysis and rainfall results, the watershed hydrology, and the groundwater flow model were presented in this study for El Qaa Plain. Also, the impact of climate change on the watershed basin in high-stress regions for different RP of 10, 25, 50, and 100 years were considered.

Estimation of watershed hydrograph for different recurrence periods

Table 3 presents the WMS results for the El Aawag watershed considering 10, 25, 50, and 100 years of RP. The results of peak discharge reached 7.77 m^3 s^{-1}, 100.78 m^3 s^{-1}, 281.23 m^3 s^{-1}, and 587.10 m^3 s^{-1} for the different RP compared with 2.49 m^3 s^{-1} in 2014.

In contrast, the flood annual volume reached 328,428 m^3, 4,872,530 m^3, 12,760,832 m^3, and 25,432,076 m^3 at RP of 10, 25, 50, and 100 years, respectively, compared with 89,892 m^3 in 2014, as shown in Table 3. These results suggest that this freshwater water would have been lost without using rainwater harvesting in such desert regions as the El Aawag watershed.

Management of watershed for different sub-basins

Figure 8a presents intensity–duration–frequency (IDF) and the infiltration rates for the El Qaa plan. The initial and constant infiltration rates reached 1.23 mm hr^{-1} and 0.09 mm hr^{-1}, respectively. The rainwater harvesting plan for the El-Aawag watershed is a chance to increase the water infiltration in the El Qaa groundwater system

Table 3 Runoff discharge for W. El Aawag watershed

Runoff Scenario	2014	10 Y	25 Y	50 Y	100 Y
Precipitation (cm)	17.05	18.80	30.10	40.70	53.40
Peak Flow (m^3 s^{-1})	2.49	7.77	100.78	281.23	587.10
Flood Volume (m^3)	89,892	328,428	4,872,530	12,760,832	25,432,076

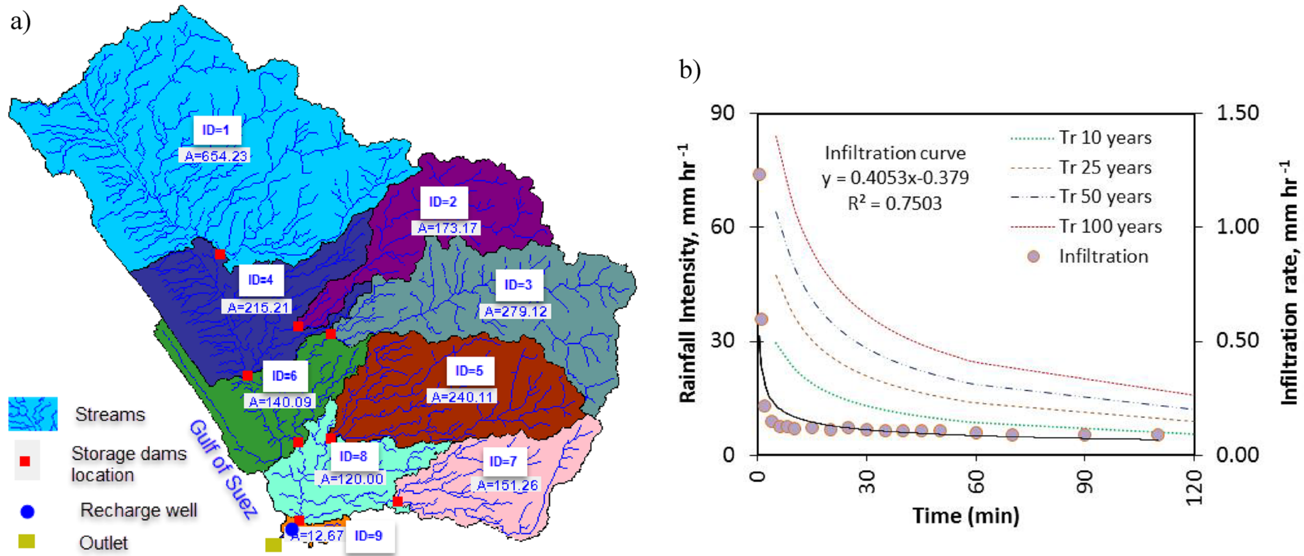

Fig. 8 El Aawag basin: **a** the location of storage dams and recharge well used for the sub-basins watershed, and **b** rainfall intensity and infiltration rates

Table 4 Proposed peak flow discharge and volume of recharge dams and wells

Basin ID	Area	10 Y		25 Y		50 Y		100 Y		Recharge
	Km^2	Q_{10} (m^3 s^{-1})	V_{10} (m^3)	Q_{25} (m^3 s^{-1})	V_{25} (m3)	Q_{50} (m^3 s^{-1})	V_{50} (m^3)	Q_{100} (m^3 s^{-1})	V_{100} (m^3)	Type
1	654.23	2.99	108,199.80	42.01	1,605,250.80	124.57	4,204,040.70	269.14	8,378,573.40	Dam
2	173.17	0.83	28,641.60	12.63	424,904.40	39.07	1,112,799.60	85.47	2,217,778.20	Dam
3	279.12	0.9	35,593.20	11.88	528,057.00	33.85	1,382,941.80	71.44	2,756,190.60	Dam
4	215.21	1.33	46,164.60	20.4	684,851.40	63.16	1,793,566.80	138.1	3,574,553.40	Dam
5	240.11	0.6	23,166.00	8.04	343,729.80	23.15	900,223.20	490.8	1,794,124.80	Dam
6	140.09	1.15	39,713.40	17.52	589,122.00	54.23	1,542,893.40	118.62	3,074,950.80	Dam
7	151.26	0.72	25,014.60	10.65	371,143.80	32.47	972,007.20	70.96	1,937,174.40	Dam
8	120	0.52	19,843.20	6.91	294,422.40	19.9	771,051.60	42.22	1,536,708.60	Dam
9	12.67	0.06	20.97	0.9	31,091.40	2.73	81,415.80	5.99	162,261.00	Well

(Elewa et al. 2023). The hydrological model was carried out to estimate groundwater harvesting for nine sub-basins. Table 4 shows sub-basin results for the RP of 10, 25, 50, and 100 years. Sub-basins # 1, #2, #3, #4, #5, #6, #7, and #8 were selected for storage recharge dam. In contrast, sub-basin # 9 was chosen to recharge the well due to the low volume of water harvesting at this sub-basin #9 (Table 5). The selection of the dams was based on a recharge pond or reservoir because the top layer is Quaternary and consists of gravel, sands, clays, and sandy clays, which have high permeability with an average value of 23.9 m day^{-1}. Figure 8b presents the location of the protection structures using nine recharge dams and one recharge well.

El Qaa groundwater modeling results

Model calibration is essential for predicting groundwater levels under different scenarios. This step includes comparing the simulated groundwater system with the observed levels for a well. The current model calibration process has been performed through several trials by adjusting the hydraulic conductivity based on steady-state nonlinear conditions.

Figure 9a shows the difference in groundwater heads between the calculated heads (MODFLOW) and observed values for 22 observation wells by field investigation. The groundwater head residuals between the simulated wells ranged from -0.05 m to 1.19 m. The mean and absolute

Table 5 Proposed elevation and volumes for recharging dams and wells

Dam#1		Dam#2		Dam#3		Dam#4		Dam#5		Dam#6		Dam#7		Dam#8	
Elevation (m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)	Elevation(m)	Vol. (MCM)
62.42	2.40	86.77	0.01	124.5	0.00	42.5	0.50	36.5	0.51	32.5	1.84	99.5	0.07	9.33	0.01
62.61	2.59	87.58	0.01	125.74	0.00	42.84	0.58	36.68	0.56	32.55	1.90	99.95	0.09	9.58	0.01
62.8	2.81	88.38	0.02	126.97	0.00	43.18	0.65	36.87	0.61	32.61	1.97	100.39	0.11	9.82	0.02
62.99	3.03	89.18	0.04	128.21	0.00	43.53	0.73	37.05	0.66	32.66	2.03	100.84	0.13	10.07	0.03
63.17	3.26	89.98	0.06	129.45	0.01	43.87	0.83	37.24	0.71	32.71	2.10	101.29	0.16	10.31	0.05
63.36	3.50	90.78	0.10	130.68	0.01	44.21	0.93	37.42	0.76	32.76	2.16	101.74	0.21	10.56	0.07
63.55	3.77	91.58	0.14	131.92	0.02	44.55	1.04	37.61	0.82	32.82	2.23	102.18	0.26	10.81	0.12
63.74	4.09	92.38	0.19	133.16	0.04	44.89	1.18	37.79	0.88	32.87	2.29	102.63	0.32	11.05	0.17
63.93	4.42	93.19	0.26	134.39	0.08	45.24	1.31	37.97	0.95	32.92	2.36	103.08	0.40	11.3	0.23
64.12	4.77	93.99	0.35	135.63	0.13	45.58	1.46	38.16	1.02	32.97	2.43	103.53	0.48	11.54	0.30
64.3	5.12	94.79	0.47	136.87	0.20	45.92	1.64	38.34	1.09	33.03	2.50	103.97	0.59	11.79	0.41
64.49	5.49	95.59	0.61	138.11	0.29	46.26	1.82	38.53	1.16	33.08	2.57	104.42	0.69	12.03	0.53
64.68	5.94	96.39	0.79	139.34	0.39	46.61	2.02	38.71	1.24	33.13	2.64	104.87	0.83	12.28	0.68
64.87	6.39	97.19	0.99	140.58	0.53	46.95	2.26	38.89	1.33	33.18	2.71	105.32	0.97	12.53	0.84
65.06	6.86	97.99	1.21	141.82	0.75	47.29	2.50	39.08	1.41	33.24	2.79	105.76	1.15	12.77	1.05
65.25	7.33	98.79	1.45	143.05	1.08	47.63	2.78	39.26	1.50	33.29	2.86	106.21	1.34	13.02	1.28
65.43	7.82	99.6	1.71	144.29	1.51	47.97	3.10	39.45	1.59	33.34	2.94	106.66	1.55	13.26	1.52
65.62	8.37	100.4	1.99	145.53	2.03	48.32	3.43	39.63	1.69	33.39	3.01	107.11	1.79	13.51	1.78
65.81	8.96	101.2	2.29	146.76	2.65	48.66	3.82	39.82	1.79	33.45	3.09	107.55	2.04	13.75	2.08
66	9.55	102	2.62	148	3.42	49	4.27	40	1.89	33.5	3.17	108	2.32	14	2.39

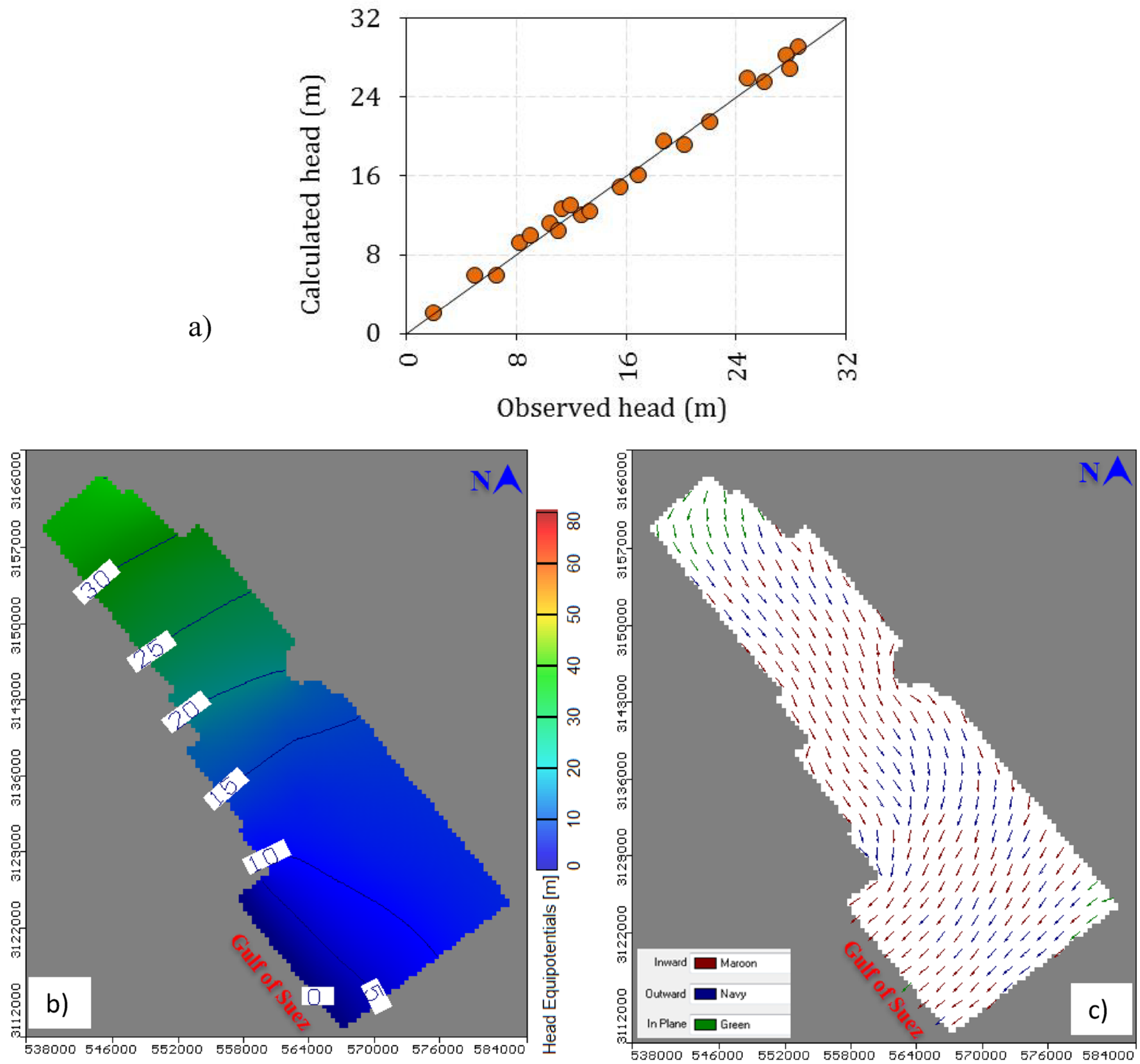

Fig. 9 Groundwater model for **a** observed and calculated heads, **b** flow heads, and **c** flow directions

residual reached -0.11 m and 0.75 m, while the standard error was 0.17 m. The root-mean-square error (RMSE) was 0.786 m with a normalization RMSE of 2.61%. The calibrated groundwater heads and the directions of groundwater flow for the El Qaa aquifer, South Sinai, Egypt, are presented in Fig. 9b and c, respectively.

The general flow direction is observed from the east to the west in the southern half of the study area. In contrast, it is from northwest to east–west. The piezometric level varies between 5 m (a.s.l) in the southwestern part, near El Tur City, to 30 m (a.s.l) in the northern part of the El Qaa aquifer. The average velocity of groundwater reached 0.13 m day^{-1}.

El Qaa groundwater recharge using RWH-MAR

The calibrated groundwater model was tested using the system of RWH-MAR at RP of 10, 25, 50, and 100 years in the El Qaa aquifer to protect the city at different recurrence intervals. Figure 10 presents groundwater flow at each interval. It indicates that increasing the recurrence interval led to increased groundwater heads differences (GWHD), reaching 0.65 m, 9.5 m, 23 m, and 39 m at RP of 10, 25, 50, and 100 years, respectively.

Thus, it is imperative not to ignore the impact of return periods when developing flash flood-prone areas. This thoughtful consideration is paramount, especially

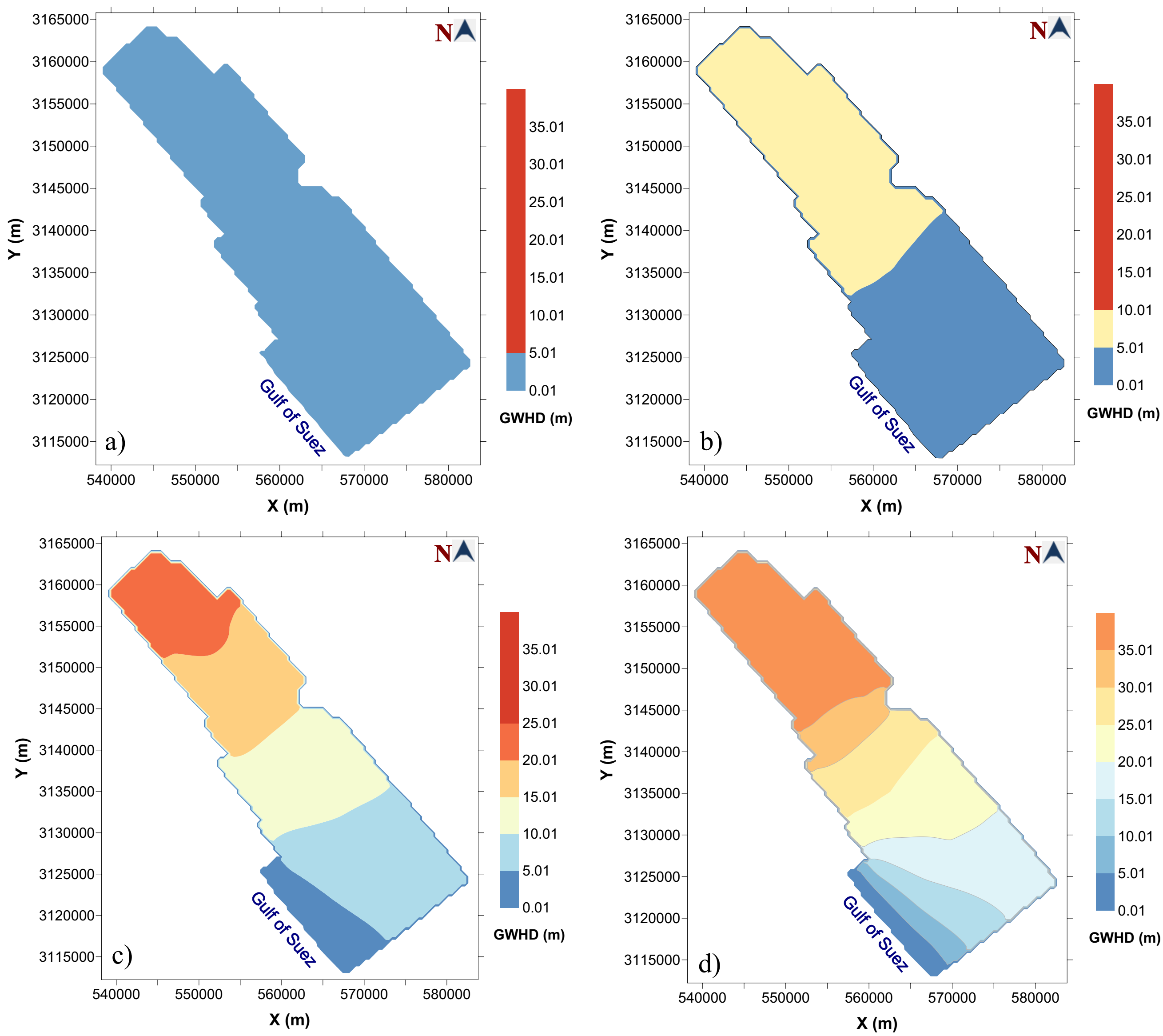

Fig. 10 Prediction groundwater heads difference (GWHD) for El Qaa aquifer at return periods **a** 10Y, **b** 25Y, **c** 50Y, and **d** 100Y

in safeguarding the freshwater resources vital to coastal regions and fortifying the critical infrastructures that underpin the resilience of these cities. By carefully accounting for return periods, urban planners and developers can implement sustainable measures that mitigate the immediate risks of flash floods and contribute to these vulnerable regions' long-term ecological and infrastructural sustainability. This holistic approach ensures that urban growth harmoniously aligns with the natural environment, fostering resilience and adaptability in unpredictable climatic events.

Discussion

The water harvesting model used changes in climatic variables to simulate future water availability. El Qaa Plain, in South Sinai, Egypt, is the largest groundwater aquifer in Sinai. It is considered the most suitable area for agricultural development and the main drinking water source for the major South Sinai cities (Mills and Shata 1989). Figure 11 shows the results of the El Aawag study area for

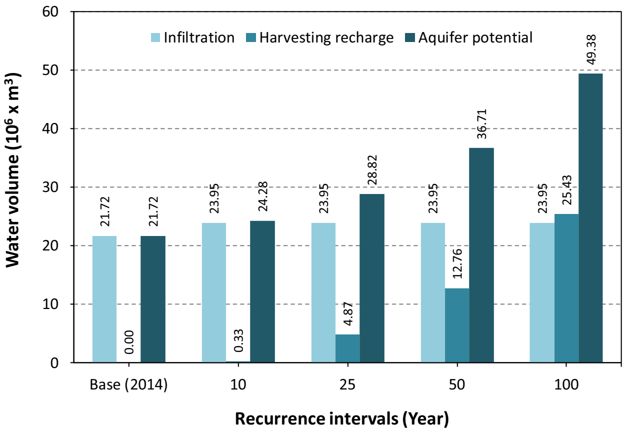

Fig. 11 El Qaa aquifer potential for different recurrence intervals

infiltration, water harvesting recharge, and aquifer potentiality for each return period.

The infiltration of rainfall through the aquifer reached 23.95 MCM, 23.95 MCM, 23.95 MCM, and 23.95 MCM at RP of 10, 25, 50, and 100 years, respectively, compared with 21.72 MCM in 2014. The hydrology losses and the aquifer recharge by the natural infiltration by 23.95 MCM before the runoff and the flash flood water go to the Gulf of Suez. Moreover, the system of RWH-MAR reached 0.33 MCM, 4.87 MCM, 12.76 MCM, and 25.43 MCM compared with 0.00 MCM in 2014, while the aquifer potentiality reached 24.28 MCM, 28.82 MCM, 36.71 MCM, and 49.38 MCM compared with 21.72 MCM at 2014. This represents a percentage change of the aquifer potentiality by + 11.78%, + 32.70%, + 69.02%, and + 127.36% at RP of 10, 25, 50, and 100 years, respectively, compared with 2014. The aquifer potentiality variation ($P—P_{2014}$) / P_{2014} was calculated, where P_{2014} is the aquifer potentiality in 2014, and P is the aquifer potentiality for the given scenario.

To mitigate the adverse impacts of escalating flooding, exacerbated by the effects of climate change, one viable strategy involves the integration of rooftop rainwater harvesting with managed aquifer recharge (Baptista et al. 2023). This approach aims to proactively address the escalating challenges of climate-induced flooding, presenting a sustainable and effective solution to safeguard water resources and mitigate the consequences of changing environmental conditions (Khanal et al. 2020). The system of Rainwater Harvesting in combination with the Managed Aquifer Recharge (RWH-MAR) approach was adopted using storage dams and recharge wells in the study area to manage the flow to the flow to the Gulf of Suez and increase the aquifer potentiality for the desert region of El Aawag plain, Sinai, Egypt, applying eight recharge dams and one recharge well (Nachson et al. 2022). The aquifer potentiality reached 24.28 MCM, 28.82 MCM, 36.71 MCM, and 49.38 MCM, compared with 21.72 MCM in 2014 for the recurrence interval of 10, 25, 50, and 100 years, respectively.

The study findings for using the system of RWH-MAR method agree with Missimer et al. (2015), who studied the aquifer recharge by the design of RWH-MAR in wadi dams using the groundwater model of MODFLOW; the results showed that about 80% of the water was lost by evaporation, while the using artificial recharge by wells improved the aquifer storage. The existing wells could store up to 1,000 m^3 day^{-1} under gravity-feed conditions and up to 3,900 m^3 day^{-1} with the shut-in of the well to produce a pressurized system. Gado and El-Agha (2020) studied the feasibility of rainwater harvesting for sustainable water management in urban areas of Egypt. The results indicated that the implementation of such RWH system has a significant impact on the regional water cycle, where the effective infiltration coefficient increased from 10% without RWH to 75% with RWH. Also, the volume of runoff decreased using RWH by around 82%. Arezoo et al. (2021) optimized the urban stormwater control strategies and assessed aquifer recharge through dry wells in an urban watershed; the results showed that the combining implementation of dry wells (DWs), bio-retention cells (BCs), and permeable pavement (PP) would increase infiltration by 19%, 15.6%, and 14%. Also, the runoff reduction rate in the presence of DWs would rise by 11.7%, 7.0%, and 6.1%. Recently, Szabó et al. (2023) studied the long-term potential and environmental impacts of rooftop rainwater harvesting coupled with shallow well infiltration, which is a local scale inexpensive solution that could contribute to easing water shortage in Danube-Tisza Interfluve (Hungary). Baptista et al. (2023) studied rooftop water harvesting for managed aquifer recharge and flood mitigation in João Pessoa, northeast Brazil. The results showed that the solutions provided mean annual estimates of aquifer recharge between 57 m^3 $year^{-1}$ and 255 m^3 $year^{-1}$ from 2004 to 2019, respectively.

The present study necessitates a thorough exploration through a comprehensive cost–benefit analysis and feasibility study concerning the construction of dams and recharge wells. This examination is crucial to accurately assess the cost-to-benefit ratio. Furthermore, addressing additional limitations, such as the assumption of uniform rainfall distribution over the basin, is imperative. It is recommended that the existing archival data be augmented by expanding the network of rainfall stations. This enhancement will contribute to refining the estimations of aquifer storage across each basin, thereby fortifying the robustness and precision of our findings.

Conclusions

Climate change in desert regions (arid and semi-arid regions) adversely impacts water supplies in regions with limited water resources. This study investigated the integration of

Rainwater Harvesting combination with the Managed Aquifer Recharge (RWH-MAR) technique for the sustainability of groundwater supplies in the aquifer of El Qaa Plain using the Watershed Modeling System (WMS) and SEAWAT software under the impact of climate change. The groundwater is recharged from precipitation and runoff from the adjacent watershed of El Awag. Results indicated that the annual rainfall reached 18.8 mm $year^{-1}$, 30.1 mm $year^{-1}$, 40.7 mm $year^{-1}$, and 53.40 mm $year^{-1}$ at return periods of 10, 25, 50, and 100 years, respectively. Also, the annual flood volume reached 328,428 m^3, 4,872,530 m^3, 12,760,832 m^3, and 25,432,076 m^3, respectively. The integrated water resources management was achieved in El Qaa plain by recharging the aquifer. This was done by proposing nine storage dams and one recharge well based on the RWH-MAR quantity and soil infiltration capacity of the sub-basins system. The rainwater for the Gulf of Suez was managed. The annual potentiality of groundwater resources in the aquifer reached 24.28 MCM, 28.82 MCM, 36.71 MCM, and 49.38 MCM for return periods of 10, 25, 50, and 100 years, respectively, compared with 21.72 MCM in 2014. For management plans and the integration between the surface and groundwater technique using rainwater harvesting, a comprehensive cost–benefit analysis and feasibility study are required to construct dams and recharge wells. Ultimately, the efficacy of the RWH-MAR system underscores its potential as a valuable tool. This effective approach holds considerable promise for policymakers in safeguarding urban areas against flash flooding, augmenting freshwater storage in arid regions, alleviating water scarcity, and promoting sustainable aquifer management.

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Declarations

Conflict of interest The authors report no declarations of interest.

References

Abbas M, Carling PA, Jansen JD, Al-Saqarat BS (2020) Flash-flood hydrology and aquifer-recharge in Wadi Umm Sidr, Eastern Desert. Egypt J Arid Environ 178:104170. https://doi.org/10.1016/j.jaridenv.2020.104170

Abd-Elaty I, Zelenakova M (2022) Saltwater intrusion management in shallow and deep coastal aquifers for high aridity regions. J Hydrol: Region Stud 40:101026. https://doi.org/10.1016/j.ejrh.2022.101026

Abd-Elaty I, Shoshah H, Zeleňáková M, Kushwaha NL, El-Dean OW (2022) Forecasting of flash floods peak flow for environmental hazards and water harvesting in desert area of El-Qaa Plain, Sinai. Int J Environ Res Public Health 19(10):6049. https://doi.org/10.3390/ijerph19106049

Abd-Elaty I, Kuriqi A, Pugliese L, Zelenakova M, El Shinawi A (2023) Mitigation of urban waterlogging from flash floods hazards in vulnerable watersheds. J Hydrol: Region Stud 47:101429. https://doi.org/10.1016/j.ejrh.2023.101429

Abd-Elaty I, Kuriqi A, Pugliese L et al (2024) Shoreline subsurface dams to protect coastal aquifers from sea level rise and saltwater intrusion. Appl Water Sci 14:49. https://doi.org/10.1007/s13201-023-02032-y

Aboelkhair H, Embaby A-A, Mesalam M (2020) Contribution of ASTER-TIR indices with geophysical and geospatial data for groundwater prospecting in El-Qaa plain area, Southern Sinai. Egypt Arabian J Geosci 13:1–13

Ahmed Ahmed MES (2012) Integrated Approach for Hydrogeologic Investigations in Africa: Inferences from Space-Borne and Land-Based Gravity, Aeromagnetic, GIS, and Remote Sensing Data.

Akib Jabed M, Paul A, Nath TK (2020) Peoples' perception of the water salinity impacts on human health: a case study in South-Eastern Coastal Region of Bangladesh. Expo Health 12:41–50. https://doi.org/10.1007/s12403-018-0283-0

Alqahtani A, Sale T, Ronayne MJ, Hemenway C (2021) Demonstration of sustainable development of groundwater through aquifer storage and recovery (ASR). Water Resour Manage 35:429–445. https://doi.org/10.1007/s11269-020-02721-2

Al-Salamah IS, Ghazaw YM, Ghumman AR (2011) Groundwater modeling of Saq Aquifer Buraydah Al Qassim for better water management strategies. Environ Monit Assess 173:851–860. https://doi.org/10.1007/s10661-010-1428-1

Arezoo B, Omid B-H, Mahdi B, Erfan G, Singh VP, Loáiciga HA (2021) Optimizing urban stormwater control strategies and assessing aquifer recharge through drywells in an urban watershed. Hydrogeol J 29:1379–1398

Baptista VSG, Coelho VHR, Bertrand GF, da Silva GBL, Caicedo NOL, Montenegro SMGL, Stefan C, Glass J, Heim R, Conrad A, Almeida CdN (2023) Rooftop water harvesting for managed aquifer recharge and flood mitigation in tropical cities: towards a strategy of co-benefit evaluations in João Pessoa, northeast Brazil. J Environ Manage 342:118034. https://doi.org/10.1016/j.jenvman.2023.118034

Bear J, Cheng AHD, Sorek S, Ouazar D, Herrera I (Eds.). (1999). Seawater intrusion in coastal aquifers: concepts, methods and practices (Vol. 14). Springer Science & Business Media.

Chahinian N, Moussa R, Andrieux P, Voltz M (2005) Comparison of infiltration models to simulate flood events at the field scale. J Hydrol 306:191–214

Chow VT, Maidment DR, Mays LW (1988) Applied Hydrology, International. McGraw-Hill Book Company, New York

Conoco (1987) Geologic Map of Egypt. Egyptian General Authority for Petroleum (UNESCO Joint Map Project), 20 Sheets, Scale 1:500 000. Cairo, Egypt

Dillon P (2005) Future management of aquifer recharge. Hydrogeol J 13:313–316. https://doi.org/10.1007/s10040-004-0413-6

El Shinawi A, Kuriqi A, Zelenakova M, Vranayova Z, Abd-Elaty I (2022) Land subsidence and environmental threats in coastal aquifers under sea level rise and over-pumping stress. J Hydrol 608:127607

Elbarbary S, Araffa SAS, El-Shahat A, Zaher MA, Khedher KM (2021) Delineation of water potentiality areas at Wadi El-Arish, Sinai, Egypt, using hydrological and geophysical techniques. J Afr Earth Sc 174:104056

Elbeih SF (2015) An overview of integrated remote sensing and GIS for groundwater mapping in Egypt. Ain Shams Eng J 6:1–15. https://doi.org/10.1016/j.asej.2014.08.008

Eldeeb HMG (2019) Assessment of Surface and Groundwater Interaction Using Field Measurements: A Case Study of Dairut City, Assuit, Egypt. Journal of Engineering Science and Technology (JESTEC) School of Engineering, Taylor's University.

Elewa HH, Qaddah AA (2011) Groundwater potentiality mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. Hydrogeol J 19:613–628

Elewa HH, Nosair AM, Zelenakova M, Mikita V, Abdel Moneam NA, Ramadan EM (2023) Environmental sustainability of water resources in coastal aquifers, case study: El-Qaa Plain, South Sinai Egypt. Water 15(6):1118. https://doi.org/10.3390/w15061118

El-Fakharany MA, Mansour NM (2021) Morphometric analysis and flash floods hazards assessment for Wadi Al Aawag drainage Basins, southwest Sinai. Egypt Environ Earth Sci 80:168. https://doi.org/10.1007/s12665-021-09457-1

El-Rawy M, Abdalla F, El Alfy M (2020) Water Resources in Egypt. In: Hamimi Z, El-Barkooky A, Martínez Frías J, Fritz H, Abd El-Rahman Y (eds) The Geology of Egypt. Springer International Publishing, Cham, pp 687–711

Eltahan AMH, Abd Elhamid AMI, Abdelaziz SM (2021) Multivariate statistical analysis of geomorphological parameters for Sinai Peninsula. Alexandria Eng J 60(1):1389–1402. https://doi.org/10.1016/j.aej.2020.10.059

Erturk ALI, Gurel M, Baloch MA, Dikerler T, Varol E, Akbulut N, Tanik A (2006) Application of watershed modeling system (WMS) for integrated management of a watershed in Turkey. J Environ Sci Health, Part A 41:2045–2056. https://doi.org/10.1080/10934520600780693

Gaafar IM, Abdrabboh A, Alshami AS (2018) Gamma-ray spectrometric investigation of north El-Tor area, southwestern Sinai. Egypt NRIAG J Astro Geophys 7:390–398. https://doi.org/10.1016/j.nrjag.2018.03.003

Gado TA, El-Agha DE (2020) Feasibility of rainwater harvesting for sustainable water management in urban areas of Egypt. Environ Sci Pollut Res 27:32304–32317. https://doi.org/10.1007/s11356-019-06529-5

Ghazaw Y (2009). Harvesting runoff from rainfall for groundwater recharge in Saudi Arabia. In: The International Conference on Water Conservation in Arid Regions ICWCAR09, King Abdulaziz University, Water Research Center, Jeddah

Gitika, T., Saikia, R., 2014. Estimation of surface runoff using NRCS curve number procedure in Buriganga Watershed, Assam, India-A geospatial approach. Internet Res. J. Earth Sci. 2 (5), 1–7

Gülbaz S, Kazezyılmaz-Alhan Cevza M, Bahçeçi A, Boyraz U (2019) Flood modeling of Ayamama River watershed in Istanbul. Turkey J Hydrol Eng 24:05018026. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001730

Guo W, Langevin CD (2002). User's guide to SEAWAT: a computer program for simulation of three-dimensional variable-density ground-water flow (Vol. 1, No. 434). US Geological Survey.

Hernandez J (2014). Monitoring water disposal wells use WirelessHART transmitters; Industrial Ethernet Book Issue 92 (9).

Ibn Ali Z, Triki I, Lajili-Ghezal L, Zairi M (2017) A method to estimate aquifer artificial recharge from a hill dam in Tunisia. J Arid Land 9:244–255

Ibrahim AS, Al Zayed IS, Abdelhaleem FS, Afify MM, Ahmed A, Abd-Elaty I (2023) Identifying cost-effective locations of storage dams for rainfall harvesting and flash flood mitigation in arid and semi-arid regions. J Hydrol: Region Stud 50:101526

INOWAS (2023) Managed aquifer recharge. https://www.inowas.com/mar/

IPCC 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland,

Jeong HY, Jun S-C, Cheon J-Y, Park M (2018) A review on clogging mechanisms and managements in aquifer storage and recovery (ASR) applications. Geosci J 22:667–679. https://doi.org/10.1007/s12303-017-0073-x

Jha AK, Bloch R, Lamond J (2012) Cities and flooding: a guide to integrated urban flood risk management for the 21st century. World Bank Publications

JICA (1999) South Sinai groundwater resources study in the Arab Republic of Egypt. Ministry of Public Works and Water Resources, Cairo, Egypt, Water resources research Institute

Jonkman SN (2005) Global perspectives on loss of human life caused by floods. Nat Hazards 34:151–175

Khanal G, Thapa A, Devkota N, Paudel UR (2020) A review on harvesting and harnessing rainwater: an alternative strategy to cope with drinking water scarcity. Water Supply 20:2951–2963. https://doi.org/10.2166/ws.2020.264

Langevin CD, Shoemaker WB, Guo W (2003) Modflow-2000, the US geological survey modular ground-water model--documentation of the SEAWAT-2000 version with the variable-density flow process (VDF) and the integrated MT3DMS transport process (IMT).

Langevin CD (2009) SEAWAT: A computer program for simulation of variable-density groundwater flow and multi-species solute and heat transport. US Geological Survey

Masoud M (2015) Rainfall-runoff modeling of ungauged Wadis in arid environments (case study Wadi Rabigh—Saudi Arabia). Arab J Geosci 8:2587–2606. https://doi.org/10.1007/s12517-014-1404-0

McDonard MG (1988) A modular three-dimensional finite-difference ground water flow model. Techniques of water-resources investigations of the US Geological survey.

Mills AC, Shata A (1989) Ground-water Assessment of Sinai. Egypt Groundwater 27:793–801

Misra AK (2019) Rainwater Harvesting and Artificial Recharge of Groundwater. In: Sikdar PK (ed) Groundwater Development and Management: Issues and Challenges in South Asia. Springer International Publishing, Cham, pp 421–439

Missimer TM, Guo W, Maliva RG et al (2015) Enhancement of wadi recharge using dams coupled with aquifer storage and recovery wells. Environ Earth Sci 73:7723–7731. https://doi.org/10.1007/s12665-014-3410-7

Morad NA (2000) Rainfall-Runoff Relationship in Mountainous Areas; Case study Wadi Sudr.

Mostafa AN, Wheida A, El Nazer M, Adel M, El Leithy L, Siour G, Coman A, Borbon A, Magdy AW, Omar M (2019) Past

(1950–2017) and future (−2100) temperature and precipitation trends in Egypt. Weather and Climate Extremes 26:100225
Nachson U, Silva CM, Sousa V, Ben-Hur M, Kurtzman D, Netzer L, Livshitz Y (2022) New modelling approach to optimize rainwater harvesting system for non-potable uses and groundwater recharge: a case study from Israel. Sustain Cities Soc 85:104097. https://doi.org/10.1016/j.scs.2022.104097
Prama M, Omran A, Schröder D, Abouelmagd A (2020) Vulnerability assessment of flash floods in Wadi Dahab Basin. Egypt Environ Earth Sci 79:1–17
SCS (1972) Snow survey and water supply forecasting. Soil Conservation Service National Engineering Handbook:1–7.
Sharma J, Ravindranath NH (2019) Applying IPCC 2014 framework for hazard-specific vulnerability assessment under climate change. Environ Res Commun 1:051004. https://doi.org/10.1088/2515-7620/ab24ed
Sherman LK (1932) Streamflow from rainfall by the unit-graph method. Eng News Record 108:501–505
Smemoe CM, Nelson EJ, Zhao B (2004) Spatial averaging of land use and soil properties to develop the physically-based green and ampt parameters for HEC-1. Environ Model Softw 19:525–535
Standen K, Costa LR, Monteiro JP (2020) In-Channel managed aquifer recharge: a review of current development worldwide and future potential in Europe. Water 12(11):3099. https://doi.org/10.3390/w12113099
Sultan SA, Mohameden MI, Santos FM (2009) Hydrogeophysical study of the El Qaa Plain, Sinai, Egypt. Bull Eng Geol Env 68:525. https://doi.org/10.1007/s10064-009-0216-z
Szabó Z, Pedretti D, Masetti M, Ridavits T, Csiszár E, Falus G, Palcsu L, Mádl-Szőnyi J (2023) Rooftop rainwater harvesting by a shallow well – Impacts and potential from a field experiment in the Danube-Tisza Interfluve. Hungary Groundwater Sustain Develop 20:100884. https://doi.org/10.1016/j.gsd.2022.100884
Tanim HA, Goharian E (2021) Developing a hybrid modeling and multivariate analysis framework for storm surge and runoff interactions in urban coastal flooding. J Hydrol 595:125670. https://doi.org/10.1016/j.jhydrol.2020.125670
USDA-TR55, (1986). Urban Hydrology for Small Watersheds, Technical Release (TR 55). United States Department of Agriculture, Soil Conservation Service, US Government Printing Office, Washington, DC, USA pp.26.https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.
Veeranna J, Jeet P (2020). Groundwater recharges technology for water resource management: a case study. In: Groundwater Management and Resources. London: IntechOpen. https://doi.org/10.5772/intechopen.93946.
Yomoto A, Islam MN (1992) Kinematic analysis of flood runoff for a small-scale upland field. J Hydrol 137:311–326
Yousif M, Hussien HM (2020) Flash floods mitigation and assessment of groundwater possibilities using remote sensing and GIS applications: Sharm El Sheikh, South Sinai. Egypt Bull Nat Res Centre 44:1–25
Yousif M, Hussien HM, Abotalib AZ (2020) The respective roles of modern and paleo recharge to alluvium aquifers in continental rift basins: a case study from El Qaa plain, Sinai. Egypt Sci Total Environ 739:139927. https://doi.org/10.1016/j.scitotenv.2020.139927
Zhang Z, Wang Z, Xu Y, Zhang Y, Guo L, Zheng Q, Tang L (2020) quantitative study on the changes of karst groundwater level and hydrochemistry in jinci spring catchment, Shanxi, China. Expo Health 12:513–525. https://doi.org/10.1007/s12403-019-00317-9
Zheng C, Wang PP (1999) MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide.