RESEARCH

Open Access

Morphotectonic controls on hydro-environmental hazards in rift basins: a case study from Southern Suez Canal Province, Egypt

Ahmed E. El-Rayes^{1*}, Mohamed O. Arnous¹, El-Arabi H. Shendi¹, Mohamed H. Geriesh¹ and Ranem A. Gharib¹

Abstract

Background The Southern Suez Canal Province (SSCP) has recently encountered hydro-environmental hazards such as water logging and soil salinization, both of which impede the efficient land use planning.

Purpose This study aims to assess the hydro-environmental threats to SSCP and identify the key factors that contribute to their occurrence. Previous research has demonstrated that the Gulf of Suez Rifting-related tectonic movements have a significant impact on the entire SSCP region. The influence of tectonic setting on the development of hydroenvironmental dangers was not examined in almost any studies.

Methods Remote sensing, GIS, hydrogeological, and geophysical techniques are used to identify and assess topographic, hydrogeological, and tectonic variables that affect hydro-environmental hazards in the SSCP.

Results This study found that the distributions of water logging, saturated soil salinization, urban areas, and vegetation cover changed more dramatically between 1984 and 2015. The expansion of water logging area (+10.68 km² rating +0.35 km²/y), saturated saline soil (+24.40 km² rating +0.79 km²/y), and urbanized area (+58.43 km² rating +1.89 km²/y) is strongly associated to the expansion of vegetation cover (+188.13 km² at a rate of 6.07 km²/y). This could imply that growing agricultural expansion and urbanization are influencing the dominance of hydro-environmental hazards in SSCP. The distribution of water logging features identified on the land cover map corresponds closely to a buried horst structure dominating the middle part of the surveyed area.

Conclusion The lowland water logging features of the SSCP provide support for the hypothesis that the buried horst structure that dominates the Miocene and pre-Miocene strata has an impact on the thickness and groundwater flow regime of the guaternary aguifer that lies above. The present study came to the conclusion that the shallow depth of groundwater, the vast expanse of newly cultivated lands, the impervious clay layer beneath the thin topsoil layer, and the low topography are the key factors influencing the development of water logging and soil salinization features in SSCP.

Keywords Hydro-environmental hazards, Morpho-tectonic controls, Shallow aquifer, Rift basins, Suez

*Correspondence: Ahmed E. El-Rayes ahmed_elrais@science.suez.edu.eg ¹ Geology Department, Faculty of Science, Suez Canal University, Ismailia 41522, Egypt

Introduction

Numerous studies have been conducted to examine the relationship between tectonic structures, geomorphology, and groundwater (Taylor and Howard 2000; Ayazi et al. 2010; Elmahdy and Mohamed 2014 and 2015; Kaplay et al. 2017; Arnous et al. 2020; Haque et al. 2020;



© The Author(s) 2023. Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.



Hegazi et al. 2023). These studies proved that structural features such as folding and faulting have a significant impact on groundwater flow patterns. The threats posed by the hydro-environment are significantly influenced by tectonic and structural features, particularly in dry and semi-arid regions (El-Rayes et al. 2017). Fractures, faults, and shear zones increase permeability and improve fluid transport through fractured and sheared rocks, which has several hydro-environmental consequences (Barton et al. 1995; Caine et al. 1996; Evans et al. 1997; Gudmundsson et al. 2001; El-Rayes et al. 2020; Arnous et al. 2020). The SSCP was greatly influenced by tectonic movements that occurred during the evolution of the Gulf of Suez rifting, which occurred in the late Oligocene and continued into the early Miocene (Bosworth et al. 1998). These tectonic deformations were crucial in forming the hydrogeological system of the SSCP. A complicated hydrogeological system was created as a result of the developed structures that split the shallow quaternary aquifer in the research area into a number of sub-hydrogeologic zones. As a consequence, the assessment of hydro-environmental hazards is mostly based on hydrogeomorphological mapping and structural element recognition utilizing geophysical measurements and remote sensing data (El-Rayes 2004, Arnous 2016, El-Rayes et al. 2017, Arnous et al. 2016). Today, rising groundwater levels are an important component in understanding the interplay between geological structures and hydrogeological processes (López and Smith 1996; Newell et al. 1999; El-Rayes and Geriesh 2002; Bedrosian et al. 2012; Borda et al. 2022). Geo-environmental hazards might take numerous forms and are spurred on by a range of natural and human factors. However, they all have the potential to pose challenges for sociocultural evolution and dangers to public safety, individual well-being, and sustainable development goals (Arnous et al. 2011 and Culshaw 2018). Land and water are the two most crucial natural resources on the earth. Therefore, careful planning and management of these resources are extremely necessary. The main strategy for locating land degradation zones and determining the source of recharge, particularly in shallow aquifers, uses hydrogeological surveys, geophysical methods, Remote Sensing (RS), and Geographic Information System (GIS) technology (Arnous and Green 2015; Arnous et al. 2015; El-Rayes et al. 2017; Moubarak et al. 2021). Furthermore, because of the severe environmental repercussions of human and natural activities, it is vital to monitor and detect changes in land cover in order to ensure sustainable development (El-Rayes et al. 2023). This rise in water level causes several hydroenvironmental consequences, including soil salinization, water pollution, water logging, and land degradation. In comparison to many conventional methods, remote sensing, GIS, and geophysical techniques have been shown to be more effective at determining how salinized soil and water logging are affected by rising water levels (Metternicht and Zinck 2003; Arnous et al. 2017; Singh 2022; Srinivasan et al. 2022). They could thus provide reasonably practical, informative, and professional rapid assessment tools for locating, monitoring, and precisely mapping structural elements, water recharge zones, land use/cover classes, and identifying the impacts of hydroenvironmental hazards (Arnous et al. 2015; Geriesh et al. 2015; El-Rayes et al. 2017). Geospatial and geophysical techniques should be used to locate, assess, and map the hydro-environmental danger features. In this case, the hydrogeological and structural influencing factors were integrated using a geospatial and geo-database system. Therefore, the qualitative and quantitative hazard potentiality of each hydro-environmental feature are determined by the strength of the influencing factor and the vulnerability of the landscape (Alexander 1997; Cutter et al. 2003; Bajracharya et al. 2007; Goswami and Pant 2008; Ebert et al. 2009; Rawat et al. 2011; Arnous et al. 2011; Arnous and Green 2015; Omran et al. 2021; Arnous and Mansour 2023).

Recently, the unwise direct and indirect activities affecting the environment are endangering the SSCP. Due to the rising groundwater level induced by these activities, there were numerous hydro-environmental and soil degradation threats. Water logging and soil salinization pose the biggest obstacles to the development of urban, industrial, agricultural, and infrastructural projects. The unique feature of this study is the development of an integrated framework based on historical seismological events that utilizes many tectonic, hydro-environmental, and topo-hydrological data sets to provide a regional approach to multi-hazard exposure mapping in Rift basins.

The goal of this study is to assess the hydro-environmental hazards that threaten SSCP and to identify the main factors that influence their occurrence. The primary goal of the research is to assess the impacts of buried tectonic features on groundwater flow regime and model the hydro-environmental hazards of the SSCP. This will be accomplished by analyzing, processing, and integrating hydrogeological, geophysical, and remotely sensed data.

Study area

The SSCP is one of the worst affected by water logging, soil salinization, and land degradation in Egypt (Youssef et al. 2021, Arnous and Mansour 2023). It is located in the Egyptian Eastern Desert, near Suez City. It has a total surface area of 1632 km² and is enclosed by Longitudes 32°22' to 32°40'E and Latitudes 29°52' to 30°16'N. It is



Fig. 1 Location map A and satellite image B of the SSCP

bordered on the north by Bitter Lakes, on the south by Suez City and G. Ataqa, on the east by Sinai, and on the west by G. Geneifa (Fig. 1).

The SSCP is classified as having a desert climate since there is primarily no annual rainfall, and the annual average temperature is 22.7 °C. May experience the driest weather because there hasn't been any rain in that month. The wettest month is November; with an average rainfall of 20 mm. January has the lowest annual average temperature (14.8 °C), while August is the warmest month. In the SSCP, the rate of evaporation generally declines toward the east, with a total annual rate of 98.5 mm. By Suez meteorological station records, the minimum relative humidity is 45.4% and the maximum is 59.9% (Abdel Basset and Hasanean 2006). For the bulk of the year, the SSCP is dominated by wind patterns from the NW, N, and NE (Suez Canal University and UNEP, 1997). The SSCP stands out because of its high wind speed on the Gulf of Suez shore, where wind speeds reach as high as 11.9 m/s.

Geology of the SSCP

The current work employs many effective processing techniques in an attempt to discriminate the rock units in the SSCP using enhanced RS data. The CONOCO geologic map of Egypt (1983) and some previous studies (Barron 1907, Hume 1925, Sadek 1926, Abdallah and Abd El-Hady 1966, and El-Akaad and Abdallah 1971), along with the enhanced satellite images, were used to generate the geological map of the SSCP



Fig. 2 Geological map of the SSCP created by combining interpreted enhanced TM images with the CONOCO geological map of Egypt

(Fig. 2). Lithologically, the SSCP covered by a sedimentary succession ranging in age from Cretaceous up to Recent (Fig. 2). The Cretaceous rocks at Gabal Ataqa are composed of dolomitic and marly limestones, shales, and sandstones. The cores of Gabal (G.) Ataqa and G. Geneifa are composed of Eocene limestone and marl with thin clay laminations. The Oligocene rocks are represented by continental sands and gravels, as well as volcanic basalt sheets exposed in the G. Geneifa. The Early Miocene sediments in the Geneifa area are primarily composed of limestone, sandstone, and gypseous clay interbeds that sit uncomfortably on top of the Oligocene sand and gravel (Barakat and Aboul Ela 1971). Upper Miocene rocks are exposed in some areas of G. Geneifa, and they are primarily composed of non-marine sand sediments, sandstones, flints, pebbles, gravels, and occasionally some sandy limestones. These rocks contain some silicified wood (Abdallah and Abd El-Hady 1966). Quaternary deposits in the Isthmus Stretch's lowlands include aeolian sands, alluvium gravels with gypsum lenses, marches and sabkha deposits, and salt crust of varying thickness. Recent sediments exist in the SSCP in the form of sand dunes, limes, sands and clay deposits. Windblown sands and wadi deposits form a thin superficial layer (Fig. 2).

The exposed rock units are stratigraphically divided between pre-rift and syn-rift sequences (Strougo and Abd-Allah 1990; Sallam et al. 2015). The former is composed of Eocene rocks and can be further divided into Observatory, Qurn, wadi Garawi, and wadi Hof formations. The latter is represented by Oligocene and Miocene strata which are unconformably overlain by reworked Pliocene carbonates and Quaternary clastic deposits composed of poorly lithified sands, gravels, and quaternary alluvium (Fig. 3).

Tectonic environment of SSCP

The overall structure of the Northwestern Gulf of Suez Rift basin, comprising the SSCP, is made up of a wide horst relay zone that runs between conjugate divergent border normal faults. The key factors controlling synsedimentation at the northern Gulf of Suez rift are the created horst relay zones via the development and propagation of normal faults (Henaish et al. 2023). The primary fault groups WNW–ESE, ENE–WSW, E–W, NW–SE,



Fig. 3 Simplified stratigraphic sequence of the SSCP (adapted from Moustafa and Abd-allah 1991)

NE-SW, and NNE-SSW are the dominant structural elements that influence and control the SSCP (Fig. 2). The E–W faults are the oldest and most likely pre-Miocene in age. The WNW–ESE faults are younger than the E–W faults and clearly affected Miocene rocks. Furthermore, the NE–SW structural fault trend is younger than the preceding two systems, and it is likely that it influenced the Quaternary sediments. Due to the drift of Arabia away from Africa, Miocene and post-Miocene extension in northern Egypt created a significant number of NW–SE oriented normal faults and rejuvenated the E–W oriented faults in the Cairo-Suez district by dextral transtension (Moustafa et al. 1998). These faults span over the basal portion of the Quaternary alluvial sediments in a similar Gulf of Suez parallel trend, indicating



Fig. 4 Seismic epicenters along the SSCP from 1904 to 2017 for events with $ML \le 4$ (Compiled catalog from the International Seismological Centre (ISC), and the Egyptian National Seismic Network (ENSN), coupled with prevalent fault trends

a recent Quaternary reactivation episode. These tendencies have been revived, according to recent seismicity data acquired over the SSCP (Fig. 4) and revealing seismic activity along the NW–SE and E–W fault lines. These faults are prevalent faults with a minor amount of strike-slip movement (Badawy 2005; Abou Elenean 2007). The Cairo-Suez district, including the SSCP, experienced active crustal deformation and volcanism during the opening of the Red Sea from the Oligocene to the Middle Miocene, resulting in deeply buried complex fault and fold structures of the Syrian-Arc System (Zain El-Din et al. 1994, and Hegazi and Omran 1998). This event is symbolized by a collection of normal faults with a N0-40W trend that are also connected to the Gulf of Suez rifting.

Geomorphology of SSCP

Understanding the geomorphological setting of the SSCP is essential for the sustainable groundwater management and recognizing the hydro-environmental hazards. Hydro-geomorphological features are often utilized to characterize groundwater potential and select ideal sites for water management practices. The landscape of the SSCP is known to be greatly influenced by the tectonic activity of the Gulf of Suez Rifting as well as the climatic changes that influenced the region throughout the successive wet and dry cycles of the Pleistocene period (El-Fayoumy 1968, El-Shazly et al. 1975, Moustafa and Khalil 1994, Hussein 2001, Youssef and Abdallah 2003, Arnous 2004, El-Hefnawy et al. 2006, Arnous et al. 2011, Hagag and Obermeyer 2016).

The SSCP is primarily distinguished by a low elevation of around 1 m above sea level, but the southern and western borders are comparatively of higher relief, ranging from a few meters to the north and increase up to more than 870 m above sea level at G. Ataqa via the southwestern ward slope (Fig. 5). Few spots in the lowlands surrounding the Isthmus Stretch have very low relief down to one meter below sea level and are covered by sabkha deposits.

A geomorphological map is produced by differentiating the main geomorphological components of the SSCP from DEM and enhanced satellite data. The SSCP has eight geomorphic components, including structural ridges, structural tableland, semi-flat terrain, isthmus length, low land with aeolian sand dunes, sand dunes belt, lakes and ponds, and Sabkha deposits (Fig. 6). The majority of the SSCP is located in the semi-flat terrain and lowlands of the El Dakruri depression. Exceptionally, a few zones of land rise up to the south at G. Ataqa (855 m), to the west at G. Geneifa (265 m), and to the northeast where sand dunes are developing (El-Fayoumy 1968, Shata and El-Fayoumy 1970, El-Shazly et al. 1975,



Fig. 5 The Digital Elevation Model (DEM) of the SSCP

El-Ibiary 1981, Ramadan 1984, Gereish 1989, Arnous 2004, El-Omla and Aboulela 2012, Arnous 2013, Arnous and Green 2017). The SSCP comprises several ponds, marshes, and sabkhas, but Youssif El-Sebaay Water Pond stands out since it was produced as a result of extensive agricultural developments and the application of flood irrigation techniques. Numerous wadis (dry streams) drain the SSCP, their bottoms filled with fluvio-marine sediments and alluvial deposits. The most important wadis (W) are W. Abu-Hassa, W. Nour Saloum, W. Ghali and W. El-Mr (Fig. 7).

Materials and methods

The current research utilizes four distinct multi-temporal Landsat 5, 7, and 8 data types to monitor and evaluate the hydro-environmental threats affecting the SSCP. ASTER GDEM was also used to create geomorphological, drainage, and groundwater flow maps. The geographic positioning system (GPS) is used for surveying and projecting the location of water points and soil samples. The USGS website (https://earthexplorer.usgs.gov) was used to download satellite data for Path P176/R39 as "Landsat 7 Enhanced Thematic Mapper" (ETM7+) and "Landsat 8 Operational Land Imager" (OLI) dated 1984, 2000, and 2015, with spatial resolution of 30 m for pixel size. Tables 1, 2, 3 outline the overall properties of the Landsat TM, ETM+7, and OLI data. The images encompassing



Fig. 6 Geomorphological map of the SSCP created using enhanced satellite images

the SSCP were mosaicked to provide a complete view of the investigated area, and then a subset for the area of study was extracted.

NASA's Terra mission launched the ASTER sensor in December 1999. It can collect stereo-image data (ASTER GDEM) with a base-to-height ratio of 0.6 by using its near-infrared spectral region and nadir-viewing and backward-viewing lenses. The horizontal plane has a spatial resolution of 15 m. The nadir-looking visual and near-infrared (VNIR) image from ASTER comprises 4100 samples by 4200 lines, which corresponds to a 60-by-60-km (km) ground region. Remote sensing and digital image processing, which involve the manipulation and interpretation of digital images, are used to detect, map, and monitor the hydro-environmental hazards that dominate the SSCP. Layer stack, subset, geometric correction, and atmospheric corrections are all components of image pre-processing. Image processing and enhancement techniques include contrast stretching, Principal Component Analysis (PCA), band rationing, and spatial filtering. The procedure required processing the ASTER GDEM data with shaded relief at azimuth angles of 0°, 45°, 90°, and 135°, and then overlaying the outcomes of the hill shading process to enable seeing the DEM from



Fig. 7 Drainage map of the SSCP extracted from ASTER GDEM

Table 1	Properties of	Landsat TM data	(NASA 1998)
---------	---------------	-----------------	-------------

 Table 2
 Properties of Landsat ETM + 7 data (NASA 2003)

				Danu no	wavelength	
Band no	Wavelength	Spectral response	Resolution (m)		interval (µm)	
	interval (µm)		1	1	0.45-0.52	
1	0.45-0.52	Blue-Green	30	2	0.52-0.60	
2	0.52-0.60	Green	30	3	0.63-0.69	
3	0.63-0.69	Red	30	4	0.76-0.90	
4	0.76-0.90	Near IR	30	5	1.55-1.75	
5	1.55-1.75	Mid-IR	30	6	10.40-12.50	
6	10.40-12.50	Thermal IR	120	7	2.08-2.35	
7	2.08-2.35	Mid-IR	30	8	0.52-0.90	

Band no	Wavelength Spectral response interval (μm)		Resolution (m)
1	0.45-0.52	Blue-Green	30
2	0.52-0.60	Green	30
3	0.63-0.69	Red	30
4	0.76-0.90	Near IR	30
5	1.55-1.75	Mid-IR	30
6	10.40-12.50	Thermal IR	60
7	2.08-2.35	Mid-IR	30
8	0.52-0.90	Pan	15

Table 3 Properties of Landsat 8 (OLI) data (NASA 2013)

Band no	Wavelength interval (µm)	Spectral response	Resolution (m)
1	0.43-0.45	Coastal/Aerosol	30
2	0.45-0.52	Blue-Green	30
3	0.52-0.60	Green	30
4	0.63-0.69	Red	30
5	0.84-0.88	Near IR	30
6	1.56-1.66	SWIR-1	30
7	2.10-2.30	SWIR-2	30
8	0.50-0.68	Pan	15
9	1.36-1.39	Cirrus	30
10	10.30-11.30	Thermal IR-1	100
11	11.50-12.50	Thermal IR-2	100

all attainable angles. Additionally, image classification is used to define the relevant classes in the mapped area. Finally, change detection and post classification comparison techniques are used to identify differences in specific feature areas seen at various times. The rate of change is determined, and the hydro-environmental implications are assessed. ERDAS Imagine 14, ArcGIS 10.3 software were used for all operations.

Gravity and magnetic potential field geophysical techniques are used to successfully delineate both shallow and deeply buried structural features. The SSCP has a Bouguer gravity map as well as a Reduced to the Pole (RTP) magnetic map (Aero-Service 1984). The automatic processing of these maps with the proper software yielded residual and regional anomaly maps, which could recognize both shallow and deep-seated structures (Nabighian 1972; Phillips 2002). On the other hand, the electrical resistivity geophysical method has successfully been employed to delineate lithological variations in near surface sediments as well as structural features impacting subsurface sediment (Zhu et al. 2009). Vertical Electrical Soundings (VES) measurements were conducted with an Earth Resistivity Meter (PSI). The general characteristics of this device made it suitable for use in the study area (user manual). The maximum current electrode distance used in the Schlumberger array was 120 m, which is long enough to reach a depth of roughly 20 m (Zohdy 1974). When the VES is proposed with a thorough understanding of the geological, geomorphologic, and hydrogeological environments, as well as the water table conditions and topography in a specific location, accurate and reliable results have been obtained (Kavidha and Elangovan 2013; Panda et al. 2017; Kolandhavel and Ramamoorthy 2019). In SSCP, three vertical electrical soundings were performed near water logging sites. The results of the resistivity survey were used to create geoelectric sections that showed vertical and lateral variations in electrical resistivity (Zohdy 1989), allowing any faults encountered to be identified.

The hydrogeological procedures are designed in the context of the current hydrogeological conditions of SSCP. The most significant hydrogeological and morphological features are observed in the field using a range of techniques, including groundwater and surface water level monitoring, GPS-based water point mapping, and field observations (Weight 2001). Using the data gathered, the water table map of the SSCP is developed, which displays the direction of shallow groundwater flow and the sources of recharge. Generally, the flow chart summarizing the data description and the techniques employed in the current study is shown in Fig. 8.

Results and discussion

Groundwater occurrences

The SSCP contains two major hydrogeologic environments. The first is the Quaternary aquifer, which covers the northernmost portion of the region running parallel to the Suez Canal. The second environment occupies the southern part of the research area and comprises the northern edges of the slopes that serve as the geographical extension of the northern Eastern Desert of Egypt (Fig. 6).

The Quaternary aquifer of SSCP is often semi-confined and composed of graded sand, rock fragments, and gravels with clay intercalations that occupied the semi-flat terrains of the study area (Moussa 1988, and RIGWA 1988). These clay intercalations are one of the causes of the water logging problem. The Quaternary aquifer is composed of sandstone, sand, and gravel strata at many sites of SSCP (Fig. 9). The eastern lowlands (Isthmus Stretch) of the SSCP are composed of fluvio-marine sediments (evaporatic sand facies). Regionally, the thickness of the overlying Quaternary aquifer varies as a result of faulting in the bed layers beneath.

Groundwater flow behavior

The SSCP groundwater is found in Quaternary formations along the semi-flat terrain and lowlands of the El Dakruri depression and Isthmus Stretch. The Quaternary deposits formed along the semi-flat terrain and lowlands of the El Dakruri depression consist of sandstone, sand, and gravel. These deposits spread from west to east until they were crossed by the Isthmus Stretch, which is made up of fluvio-marine evaporitic sand sediments. Moreover, the Quaternary aquifer overlies directly some types of Pliocene clay and/or Miocene rocks (Fig. 9c). The Quaternary aquifer of the semi-flat terrain was in an unconfined condition. The main source of recharge to



Fig. 8 A flow chart simplifies the data description and techniques used in the current study



Fig. 9 Quaternary sediment exposures consisting primarily of sand and gravel (A, B and D), with a clay layer beneath (C)

the SSCP's Quaternary aquifer is leakage from the irrigation canal system. The returned flow water from irrigation practices is another recharge source, as evidenced by water mounds along newly reclaimed irrigated lands to the west of the study area. Prior to the development of new cultivated lands, old satellite images clearly show the absence of any water ponds along the same sites (Fig. 10). Flood irrigation has a variety of effects: First, they initiate seepage processes that result in changes in pore water pressure inside the slope and seepage pressure as a result of potential transient seepage (Biniyaz et al. 2021; Guardiani et al. 2022). Second, because irrigation cycles run in flooding-drying cycles, the nearby lowlands material experiences wetting-drying cycles, which strengthens soil degradation (Miao et al. 2020; Liao et al. 2021).

The general hydraulic gradient of the SSCP is from the border to the Suez Canal and Bitter Lakes (Fig. 11). Because the groundwater level is higher than the sea level, the Suez Canal and Bitter Lakes act as the discharge boundary, and the groundwater flow direction is from west to both east and northeast (Fig. 11). Due to the presence of an impervious clay layer at shallow depth, the depth to the water in the east is less than 0.5 m, while in the west it is about 6 m. The poor hydraulic conductivity sediments that constitute the Quaternary aquifer in the Isthmus Stretch zone abruptly convert the contained aquifer into a semi-confined type. The aforementioned factors generate water logging, which is most noticeable close to irrigated farmland and local depressions. Because of the SSCP's high rate of evaporation, the logged water becomes more saline, and a significant amount of groundwater storage is lost due to evaporation.

According to the remotely sensed monitoring of groundwater level signals, groundwater levels in the SSCP have gradually risen since the start of irrigated agriculture in the year 2000. Dissolved salts migrate to the shallow subsurface as water levels rise by capillary action, and when water reaches the ground surface, they cause water logging. During the evaporation of water in a dry climate, salts are left behind, degrading the soil.



Fig. 10 Early satellite image from 1984 A and more recent ones from 2015 B illustrate how water logging features have expanded before and after the development of land reclamation activities

Land use/land cover analysis

The enhanced multi-temporal satellite data for the years 1984, 2000, and 2015 are used to create the LU/LC distribution maps for the SSCP. Image classification, PCA, image indices, and change detection techniques were used to identify the various LU/LC classes and the possible reasons of hydro-environmental threats (Fig. 12). The generated maps show that the SSCP is vulnerable to quick and continuous changes in numerous classes of LU/LC owing to both natural and human activities. The distributions of water logging, saturated soil salinization, and vegetation cover had the most significant changes between the years 1984 and 2000 and between the years 2000 and 2015, respectively. Water-logged areas increased by 8.32 km² (0.25% to 0.90%) between 1984 and 2000, and by 2.36 km² (0.90% to 1.07%) between 2000 and 2015. Between 1984 and 2000, saturated saline soil dropped from 53.48 to 37.59 km² (4.10% to 2.91%), and from 2000 to 2015, it grew from 37.59 to 77.88 km^2 (2.91% to 5.98%). Vegetation expanded by 43.43 km² to 75.44 km² between 1984 and 2000 (3.33% to 5.84%), and by 75.44 km² to 231.56 km² between 2000 and 2015 (5.84% to 17.78%) (Table 4).

Furthermore, the rate of change for each LU/LC class in the research area from 1984 to 2015 is assessed (Table 5). The most important areal changes between 1984 and 2015 were in the distributions of water logging, saturated soil salinization, urban areas, and vegetation cover. The growing of water logging area (+10.68 km² rating+0.35 km²/y), saturated saline soil (+24.40 km² rating+0.79 km²/y), and urbanized area (+58.43 km² rating+1.89 km²/y) is substantially connected with the increasing of vegetation cover (+188.13 km²) with an increasing rate of 6.07 km²/y. This may indicate the impact of human activities (new land cultivation and urbanization) on the dominance of hydro-environmental hazards (water logging and soil salinization) in the SSCP.



Fig. 11 Water table map of the SSCP showing the groundwater flow direction



Fig. 12 Extracted multi-temporal LU/LC classified maps of SSCP with statistical representations of each class through the years 1984, 2000 and 2015



Fig. 12 continued

Table 4 Area-evaluation of the main land use land/cover classes in SSCP through the years 1984, 2000 and 2015

Class	1984		2000		2015	
	Area (km²)	Area (%)	Area (km²)	Area (%)	Area (km²)	Area (%)
Water logging	3.28	0.25	11.60	0.90	13.96	1.07
Saline soil	118.64	9.09	106.11	8.22	60.04	4.61
Vegetation	43.43	3.33	75.44	5.84	231.56	17.78
Water bodies	184.01	14.10	184.40	14.28	184.69	14.18
Islands	1.34	0.10	0.92	0.07	1.19	0.09
Sand dunes	146.39	11.22	161.80	12.53	131.11	10.07
Mountainous area	62.13	4.76	62.05	4.81	59.82	4.59
Urban area	45.47	3.49	86.68	6.72	103.90	7.98
Bare land	646.60	49.56	564.29	43.71	438.24	33.65
Saturated saline soil	53.48	4.10	37.59	2.91	77.88	5.98

Geophysical analysis of morpho-tectonic anomalies

Gravity and magnetic data collected at any point on the ground surface reflect an integral impact of the fields generated by different causative sources in the vicinity of the measuring station and/or buried at various depths, as long as these sources have a sufficient physical contrast with their surroundings. The shape of the resulting anomalies is strongly influenced by the depths, sizes, and azimuths of their relevant causative sources. Short wavelength anomalies are produced by near-surface sources, while long wavelength anomalies are produced by deep sources (Tschirhart et al. 2013, Khalil 2016, Ekwok et al. 2020, Ejiga et al. 2021, Rao and Silpa 2023). As a result, by analyzing the shapes of the detected anomalies, the geometry of these sources can be deduced. These various anomalies are separated,

 Table 5
 Rates of change in areas of the LU/LC classes from 1984 to 2015 of SSCP

Classes	Change in areas (km ²)	Rate of change (km²/year)
Water logging	+ 10.68	+0.35
Saline soil	- 58.60	- 1.89
Vegetation	+ 188.13	+6.07
Water bodies	+0.68	+0.02
Islands	- 0.15	- 0.004
Sand dunes	- 15.28	- 0.49
Mountainous area	- 2.31	- 0.108
Urban area	+ 58.43	+1.89
Bare land	- 208.36	- 6.72
Saturated saline soil	+ 24.40	+0.79

and their depths are estimated, using the mathematical spectral analysis (Spector and Grant 1970; Kebede et al. 2021; Saada et al. 2021). This issue was addressed by using appropriate geophysical methods to locate both near-surface and deeply seated faults, which are important for figuring out the geometry of the overlying quaternary aquifer. The buried horst feature governs the geometry and thickness of the overlying quaternary aquifer, resulting in a high water level in the reservoir. As a result, the local depressions that are overlaid the horst features will be waterlogged because of the rising water level.

Airborne potential field data (gravity and magnetic) were used in this study to detect near surface and deep seated faults. Both a lateral change in the density of the subsurface rocks and variations in the Bouguer gravity values in the study area indicate the presence of faults. These faults run in three different directions: NE-SW, NW–SE, and E–W. Using the Geosoft application, the regional—residual anomaly separation procedure was applied to the Bouguer gravity map of SSCP. The regional anomaly map depicts the deep and long extension faults of the NE–SW and NW–SE trends (Fig. 13).

The residual gravity map of SSCP (Fig. 14) is distinguished by near-surface faults of different orientations (ENE–WSW and NW–SE) and limited extension. These faults have a significant role in the lateral and vertical movement of surface water, as well as occasionally ground water, which results in a challenge of water logging. It is important to note that several of these faults have alignments with water logging sites, which may be proof of the significant role they have in creating the structural criteria for water logging formation.

The magnetic map can reveal the structural lineaments on the buried basement rocks and their overlying sedimentary strata. Reduced to the pole (RTP) magnetic map is always derived from the total magnetic map where the magnetic anomalies lie directly over the subsurface causative structures. The RTP magnetic map of SSCP reveals deep seated faults in the ENE–WSW and NW–SE directions (Fig. 15). Once more, these faults are the exclusive cause of some water logging sites.

To identify both deep-seated and near-surface faults, the RTP map was further subjected to a regional-residual separation technique using the Geosoft software (Figs. 16 and 17). The relief of the Precambrian basement body is significantly impacted by the N–S, NE-SW, and E–W trends of the deeply seated faults (Fig. 16). Table 6 describes the deep-seated fault using information from the regional magnetic map.

The residual magnetic map of SSCP (Fig. 17) is distinguished by near-surface faults of different orientations (N–S and NW–SE). The geometry of the overlying Quaternary aquifer is controlled by the overall structural setting of the phanerozoic shallow succession, which can be determined through the identification of near-surface faults. Table 7 describes the near-surface fault using information from the residual magnetic map.

By using the vertical electrical sounding (VES) technology, it has been possible to better understand the subsurface geologic characteristics at several water logging sites in the SSCP. It entails injecting a high-voltage electric current into earth sediments via two current electrodes and measuring the potential difference caused by the current flow via a second set of potential electrodes. The true electrical resistivity of subsurface sediments and rock layers, as well as their depths, can be estimated using the current intensity, potential difference, and configuration factor of the used array. Using the Schlumberger Array, three vertical electrical soundings in the SSCP were measured. The current electrode distance was around 120 m, which is enough to reach a depth of roughly 20 m in the earth's layers. The three VES curves are of the 3-layer H-type (Fig. 18), and the intermediate layer of such curves has a very low resistivity value (less than 5 m), which is believed to be a layer of clay relying on the dominant surface geology. This layer prevents surface water from percolating vertically, resulting in the creation of water logging features. The presence of a low resistivity cusp in the first segment of the three curves suggests the existence of clay lenses or a lateral facies change in the surface sediment layer. The bottom layer has a relatively high resistivity and is thought to be a fractured limestone layer based on the SSCP's geology. This layer is highly fractured and could serve as a drain to help mitigate the water logging challenge.



Fig. 13 The regional gravity map of SSCP showing the distributions of deep faults of the NE–SW and NW–SE trends

32°24'0"E 32°30'0"E 32°36'0"E Bitter Lakes .0.3 0.3 30°12'0"N 30°12'0"N 30°6'0"N 30°6'0"N 30°0'0'N N"0'0°0E Suez City Gulf of Suez 29°54'0"N 29°54'0"N Legend Contour line (Value in mgal) Km Fault trace

Fig. 14 The residual gravity map of SSCP showing the distributions of near-surface faults with ENE-WSW and NW-SE trends

32°24'0"E

32°30'0"E

32°36'0"E



Fig. 15 The RTP magnetic map of SSCP showing the distributions of near-surface faults with ENE–WSW and NW–SE trends

(2023) 10:18

El-Rayes et al. Geoenvironmental Disasters



32°24'0"E



32°30'0"E

32°36'0"E

Fig. 17 The residual magnetic map of SSCP showing the distributions of near-surface faults with NW–SE and NE–SW trends

Fault trend	Designated number of faults on Fig. 16	Total no	Length (km)	Total length (km)	Lithology
N–S	6	3	24.3	61.1	Pre-Cambrian Basement rocks
	7		19.7		
	8		17.1		
NE-SW	5	2	15.3	33.7	
	3		18.4		
E–W	4	3	14.5	32.5	
	1		18		
	2		11.7		

 Table 6
 Deeply seated fault information generated from the regional magnetic map of SSCP

 Table 7
 Near-surface faults information generated from the residual magnetic map of SSCP

Fault trend	Designated number of faults on Fig. 17	Total No	Length (km)	Total length (km)	Lithology
N–S	5	2	24.3	44	Eocene to pliocene rocks
	6		19.7		
NE–SW	1	4	18.3	60.2	
	2		15.3		
	3		12		
	4		14.6		

The geological cross-sections (Figs. 19 and 20) drawn across the three VES curves revealed that the second geoelectric layer (Clay layer), which has a very low resistivity, acts as a barrier to prevent vertical percolation of the surface water, that leads to the formation of water logging features. This layer is also influenced by faults, which can act as conduits for surface water to flow downward into the underlying fractured limestone aquifer. This approach might be regarded as a potential water logging mitigation strategy.

The influence of morphotectonics on groundwater flow regime

The faulting, folding, and fractures of bedrock aquifers and their confining layers, which result in varying geometry and hydraulic properties, can have a significant impact on groundwater flow (Spottke et al. 2005; DesRoches et al. 2014; El-Rayes et al. 2017, 2020; Moore and Walsh 2021). Faults have a massive effect on groundwater flow in the Quaternary aquifer of the SSCP. The geometry of the buried graben and horst features caused by major tectonic rifting of the Gulf of Suez has a significant effect on the flow pattern and thickness of the overlaid shallow Quaternary aquifer in the SSCP (Figs. 19 and 20). The buried horst influences the geometry of the top quaternary aquifer, causing aquifer thickness to thin and groundwater levels to rise, resulting in water logging. The groundwater flow direction in the Quaternary aquifer is guided by the clay layer topped horst beneath it. When groundwater recharged and circulating in the Quaternary aquifer reaches the depth of the impermeable clay-capped horst, it is directed in part towards the east (to the Suez Canal) and the northeast (to the Bitter Lakes) (Fig. 11). Actually, the position of the groundwater level is defined by this clay-capped horst, which may be raised above the ground surface, resulting in the formation of water logging features, particularly at topographic depressions.

The influence of morphotectonics on the vulnerability to hydro-hazards

Water logging and soil salinization, caused by recent human activities at the SSCP, are now the most prevalent desertification phenomena, endangering soil fertility and causing significant water loss through evaporation. The prevailing morphological and tectonic evolution of the enclosed area has a strong influence on aquifer thickness (Rubio et al. 2007). The thickness of the Quaternary aquifer that lies on top of the buried horst structures is closely connected with the distribution of water logging sites along the SSCP (Fig. 19). The most vulnerable area to water logging and, as a consequence, soil salinization is the thin water-bearing formation zone that lies above the buried horst structure at the recharge zone (Fig. 19).

Page 23 of 28



Fig. 18 VES curves at the study area showing cusps, H-type and second layer with very low resistivity (clay layer)

The rapid recharge rate of seepage from irrigation systems and the excess irrigation water returned-flow from the recently reclaimed cultivated lands both contribute to the development of water logging at the recharge zone of SSCP. The graben faulting created a sedimentary basin filled with thick sediments that serves as a groundwater reservoir zone at the lowlands discharge border (Fig. 20).

The dynamic pattern of water logging development

The analysis of satellite images and field observations revealed that significant tracts of water logging and water ponds had formed on the low land surfaces as a result of the cultivation of broad regions in semi-flat terrains bordered by low lands. The majority of the water logged spots are dispersed in a distinct pattern that resembles local topographic depressions and thin top-soil layer. Because of the prevailing aridity, most of the western semi-flat topography has weak surface expression and is presently covered by thin Quaternary gravely sands underlain by a shallow Pliocene clay layer. The extent of seepage and water logging within the newly cultivated fields in the SSCP coincides with the automatically retrieved surface slope from the DEM. Excess irrigation water seeps through the subsurface and progressively migrates towards the lowland along the Isthmus Stretch, saturating the dormant local depressions. This significant correlation strongly suggests the influence of geomorphology and landforms on the dynamics of water logging. Local depressions focus the seepage down the surface slope via the lowlands eastward, resulting in the development of surface ponds in distant cultivated lowlands. The entire agricultural area in the SSCP was roughly 43 km² in 1984, and it expanded to 232 km² in 2015. During the same time span, waterlogged and ponded spots expanded from around 3.3 km² to nearly 14 km². The present study clearly demonstrates that development has not considered the regional physiographic setting of soil, hydrological environment, and geomorphology of agricultural regions. The agricultural fields in the SSCP are primarily planted on semi-flat topography landforms. The majority of the soils in these landforms are thin (less than 0.5 m thick), governed by structural setting, and underlain by an impervious clay layer. This means that the clay layer underneath these soils may obstruct the vertical flow of groundwater, facilitating the rapid development of water logging problems.

Conclusion

The SSCP identifies significant site impacts of the Gulf of Suez rifting as buried graben and horst structures. The resulting tectonic structures in SSCP govern the local groundwater flow regime and the hydrogeologic zonation of the overlying Quaternary aquifer. A first key step in explaining the groundwater flow regime and associated hydro-environmental hazards that prevailing in the study area is the identification of buried bedrock geometry and lateral variations in the thickness of the overlying Quaternary aquifer.

The groundwater discharge zone in the western portion of SSCP is distinguished by significant tectonic features, particularly the buried graben structures. The water table measurement revealed significant water level variations all over the eastern part of the SSCP, which was highlighted by the graben structure. This variation indicates that the graben structure serves as a basin for





Fig. 19 A geological cross-section of the SW–NE profile shows how tectonic features affect the thickness of the overlaid Quaternary aquifer (see Fig. 16 for deep faults & Fig. 17 for near surface faults locations)

groundwater accumulation at the discharge area's end of the flow path.

The local groundwater flow in the overlying Quaternary aquifer originated at the western recharge boundary, directly above the buried horst-graben structure, and became directed into the eastern lowlands and northeastern Bitter Lakes. At the western recharge zone of the SSCP, the aquifer is primarily recharged by seepage from new irrigation distributaries as well as returned-flow water from excessive irrigation water in newly reclaimed lands.

The thickness of the Quaternary aquifer overlying the buried horst structure is strongly correlated with the distribution of waterlogged sites and soil salinized zones in the SSCP. Thick water-bearing formation controlled by graben structure receives a large volume of accumulated groundwater at the discharge area on the eastern border, causing the groundwater level to rise above the ground surface, resulting in the development of water logging features. The thin water-bearing formation overlying the buried horst structure at the recharge area to the western border is the most vulnerable to water logging and, as a consequence, soil salinization.

There are significant gaps in scientific understanding of the environmental consequences of tectonic rift basins. The current study adds to closing some knowledge gaps by better understanding the impact of rift-related structures on the susceptibility to



Fig. 20 A geological cross-section of the NW–SE profile shows how tectonic features affect the thickness of the overlaid Quaternary aquifer (see Fig. 16 for deep faults & Fig. 17 for near surface faults locations)

hydro-environmental hazards. Because rift basin environment concepts are still in the early stages of study, there is no data on environmental effects are available. Mitigation and restoration of ecosystems are effective in reducing the effects of hydro-environmental hazards on soil of rift basins, which needs to be researched more in the near future.

Acknowledgements Not applicable

Author contributions

A.E.: Data analysis and interpretation of results and drafting, reviewing and submitting the original manuscript. M.O.: Data integration and GIS modeling and sharing the first draft of manuscript. E.H: Field data collection, analysis and interpretation of results and sharing the first draft. M.H.: sharing the first draft of manuscript and interpretation of results. R.A.: Collecting, analyzing and interpreting field data, as well as drafting figures.

Funding

Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB). The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Availability of data and materials

All data generated or analyzed in this study are included in the published article.

Declarations

Ethics approval and consent to participate

The authors claim to have no conflicts of interest.

Competing interests

The authors declare no competing interests.

Received: 19 March 2023 Accepted: 14 August 2023 Published online: 23 August 2023

References

- Abdallah A, Abd El-Hady F (1966) Geology of Sadat area, Gulf of Suez Egypt. Egypt J Geol Cairo 10(1):1–24
- Abou Elenean K (2007) Focal mechanisms of small and moderate size earthquakes recorded by the Egyptian national seismic network (ENSN). Egypt NRIAG J Geophys 6(1):119–153
- Aero-Service (1984) Final operational report of airborne magnetic/radiation survey in the Eastern Desert, Egypt for the Egyptian general petroleum corporation. Aero-Service, Houston, Texas, Apr, 1984, Six Volumes
- Alexander D (1997) The study of natural disasters, 1977–97: some reflections on a changing field of knowledge. Disasters 21:284–304. https://doi. org/10.1111/1467-7717.00064
- Arnous MO (2013) Geotechnical site investigations for possible urban extensions at Suez City, Egypt using GIS. Arab J Geosci 6:1349–1369. https:// doi.org/10.1007/s12517-011-0441-1
- Arnous MO (2016) Groundwater potentiality mapping of hard-rock terrain in arid regions using geospatial modelling: example from Wadi Feiran basin, South Sinai. Egypt Hydrogeol J 24:1375–1392. https://doi.org/10. 1007/s10040-016-1417-8
- Arnous MO, Green DR (2015) Monitoring and assessing waterlogged and saltaffected areas in the Eastern Nile delta region, Egypt, using remotely sensed multi-temporal data and GIS. J Coast Conserv 19(3):369–391. https://doi.org/10.1007/s11852-015-0397-5
- Arnous MO, Aboulela HA, Green DR (2011) Geo-environmental hazards assessment of the North western Gulf of Suez. Egypt J Coast Conserv 15(1):37–50. https://doi.org/10.1007/s11852-010-0118-z
- Arnous MO, El-Rayes AE, Helmy AM (2017) Land-use/land-cover change: a key to understanding land degradation and relating environmental impacts in Northwestern Sinai. Egypt J Environ Earth Sci 76:263–283. https://doi.org/10.1007/s12665-017-6571-3
- Arnous MÖ, Mansour BMH (2023) Utilizing multi-temporal thermal data to assess environmental land degradation impacts: example from Suez Canal region Egypt. Environ Sci Pollut Res. https://doi.org/10.1007/ s11356-022-22237-z
- Arnous MO, El-Rayes AE, Green DR (2015) Hydrosalinity and environmental land degradation assessment of the East Nile delta region Egypt. J Coast Conserv 19:491–513. https://doi.org/10.1007/s11852-015-0402-z
- Arnous MO, El-Rayes AE, Geriesh MH, Ghodeif K, Al-Oshari F (2020) Groundwater potentiality mapping of tertiary volcanic aquifer in IBB basin, Yemen by using remote sensing and GIS tools. J Coast Conserv. https://doi.org/ 10.1007/s11852-020-00744-w
- Arnous MO (2004) Geo-environmental assessment of Cairo-Ismailia road area, Egypt, using remote sensing and GIS. PhD thesis, Fac of Sci, Suez Canal Univ, Ismailia, Egypt 283p
- Ayazi MH, Pirasteh S, Pili AK, Biswajeet P, Nikouravan B, Shattri Mansor S (2010) Disasters and risk reduction in groundwater: Zagros mountain southwest Iran using geoinformatics techniques. Disaster Adv 3(1):51–57
- Badawy A (2005) Present-day seismicity, stress field and crustal deformation of Egypt. Egypt J Seismol. https://doi.org/10.1007/s10950-005-2190-7
- Bajracharya SR, Mool PK, and Shrestha BR (2007) Impact of climate change on Himalayan glaciers and glacial lakes. Kathmandu: international centre for integrated mountain development 119p

- Barakat MG, Aboul Ela NM (1971) Microfacies and paleoecology of Middle Eocene and younger sediments in Geneifa area, Cairo-Suez district. Egypt Egypt J Geol 14:23–24
- Barron T (1907) The topography and geology of the district between Cairo and Suez. Egypt. Surv Dept, Cairo 133p
- Barton CA, Zoback MD, Moos D (1995) Fluid flow along potentially active faults in crystalline rock. Geology 23(8):683–686. https://doi.org/10.1130/ 0091-7613(1995)023%3c0683:FFAPAF%3e2.3.CO;2
- Bedrosian PA, Burton BL, Powers MH, Minsley BJ, Phillips JD, Hunter LE (2012) Geophysical investigations of geology and structure at the Martis Creek Dam, Truckee, California. J Appl Geophys 77:7–20. https://doi.org/10. 1016/j.jappgeo.2011.11.002
- Biniyaz A, Azmoon B, Liu Z (2021) Coupled transient saturated– unsaturated seepage and limit equilibrium analysis for slopes: influence of rapid water level changes. Acta Geotech. https://doi.org/10.1007/ s11440-021-01359-7
- Borda DR, Cociuba I, Epure L, Cruceru N, Meleg IN (2022) The interplay of environment and biota in assessing the freshwater quality in karst. Diversity 14(6):475. https://doi.org/10.3390/d14060475
- Bosworth W, Crevello P, Winn RD, Steinmetz J (1998) Structure, sedimentation, and basin dynamics during rifting of the Gulf of Suez and northwestern red sea. In: Purser BH, Bosence DWJ (eds) Sedimentation and tectonics in rift basins red sea - Gulf of Aden. Springer, Dordrecht
- Caine JS, Evans JP, Forster CB (1996) Fault zone architecture and permeability structure. Geology 24(11):1025–1028. https://doi.org/10.1130/0091-7613(1996)024%3c1025:FZAAPS%3e2.3.CO;2
- CONOCO (1983) Photogeological interpretation map, scale (1:500,000). CORALI Inc., Cairo and Beni Sueif
- Culshaw CM (2018) Geohazards. In: Bobrowsky P, Marker B (Eds.): Encyclopedia of engineering geology. Encyclopedia of earth sciences series. https://link.springer.com/referencework/https://doi.org/10.1007/ 978-3-319-73568-9
- Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. Soc Sci Q 84:242–261. https://doi.org/10.1111/1540-6237. 8402002
- DesRoches A, Danielescu S, Butler K (2014) Structural controls on groundwater flow in a fractured bedrock aquifer underlying an agricultural region of northwestern new Brunswick, Canada. Hydrogeol J 22:1067–1086. https://doi.org/10.1007/s10040-014-1134-0
- Ebert A, Kerle N, Stein A (2009) Urban social vulnerability assessment with physical proxies and spatial metrics derived from air- and spaceborne imagery and GIS data. Nat Hazards 48:275–294. https://doi.org/10.1007/s11069-008-9264-0
- Abdel Basset H, Hasanean HM (2006) Heat wave over Egypt during the summer of 1998. The Int J Meteorol 31(308):133–134
- Ejiga EG, Ismail NEH, Yusoff I (2021) Implementing digital edge enhancers on improved high-resolution aeromagnetic signals for structural-depth analysis around the Middle Benue Trough. Nigeria Minerals 11:1247. https://doi.org/10.3390/min11111247
- Ekwok SE, Akpan AE, Kudamnya EA et al (2020) Assessment of groundwater potential using geophysical data: a case study in parts of cross river state, south-eastern Nigeria. Appl Water Sci 10:144. https://doi.org/10. 1007/s13201-020-01224-0
- El-Akaad S, Abdallah A (1971) Contribution to geology of Gabal Ataqa area. Ann Geol Surv Egypt 2:21–42
- El-Fayoumy IF (1968) Geology of groundwater supplies in the region east of the Nile Delta and its extension in north Sinai. Ph.D. Thesis, Fac of Sci, Geol Dept, Cairo Univ, Egypt 207p
- El-Hefnawy M, Deif A, El-Hemamy ST et al (2006) Probabilistic assessment of earthquake hazard in Sinai in relation to the seismicity in the eastern Mediterranean region. Bull Eng Geol Environ 65:309–319. https://doi. org/10.1007/s10064-006-0044-3
- El-Ibiary MG (1981) Shallow subsurface geological and geophysical studies in Lake Timsah, Suez Canal area. MSc Thesis, Fac of Sci, Tanta Univ, Egypt
- Elmahdy SI, Mohamed MM (2014) Relationship between geological structures and groundwater flow and groundwater salinity in AI Jaaw plain, United Arab emirates; mapping and analysis by means of remote sensing and GIS. Arab J Geosci 7:1249–1259. https://doi.org/10.1007/ s12517-013-0895-4
- Elmahdy SI, Mohamed MM (2015) Automatic detection of near surface geological and hydrological features and investigating their influence

on groundwater accumulation and salinity in southwest Egypt using remote sensing and GIS. Geocarto Int 30(2):132–144. https://doi.org/10. 1080/10106049.2014.883433

- El-Omla MM, Aboulela HA (2012) Environmental and Mineralogical studies of the sabkhas soil at Ismailia—Suez Roadbed, Southern of Suez canal district. Egypt Open J Geol 2:165–181
- El-Rayes AE (2004) Use of lineament analyses and joint measurements as guides for drilling high yield water wells in the basement aquifer of south Sinai. Egypt J Petroleum Min Eng 7(1):67–76. https://doi.org/10. 6084/m9.figshare.16732480
- El-Rayes AE, Arnous MO, Aziz AM (2017) Morphotectonic controls of groundwater flow regime and relating environmental impacts in Northwest Sinai. Egypt Arab J Geosci 10(18):401. https://doi.org/10.1007/ s12517-017-3188-5
- El-Rayes AE, Omran AF, Geriesh MH, Hochschild V (2020) Estimation of hydraulic conductivity in fractured crystalline aquifers using remote sensing and field data analyses: an example from Wadi Nasab area, South Sinai. Egypt J Earth Syst Sci 129:203. https://doi.org/10.1007/ s12040-020-01470-5
- El-Rayes AE, Arnous MO, Green DR et al (2023) Geo-hazards assessment of the new-found industrial communities: an example from the 10th of Ramadan industrial region. Egypt Environ Syst Res 12:21. https://doi. org/10.1186/s40068-023-00306-7
- El-Rayes AE and Geriesh MH (2002) Reasons of waterlogging around Serabium waste water treatment plant, Ismailia, Egypt. Proc. 3rd International Conference of groundwater level control inside urbanized areas, Fac Engineering, Mansoura University, Mansoura, Egypt, 17–19 Dec 2002, pp123–136. https://doi.org/10.6084/m9.figshare.16731697
- El-Shazly E, Abdel Hady M, El-Shazly MM, El-Ghawaby M, El-Khassas I, Salman A, and Morsy M (1975) Geological and groundwater potential studies of El Ismailia master plan study area. The Remote Sensing Research Project, Academy of Scientific Research and Technology, 101, Kasr El-Aini street, Cairo, Egypt. pp. 1–24
- Evans JP, Forster CB, Goddard JV (1997) Permeability of fault-related rocks, and implications for hydraulic structure of fault zones. J Struct Geol 19(11):1393–1404. https://doi.org/10.1016/S0191-8141(97)00057-6
- Geriesh MH, Balke K-D, El-Rayes AE, Mansour BM (2015) Implications of climate change on the groundwater flow regime and geochemistry of the Nile Delta. Egypt J Coast Conserv 19:589–608. https://doi.org/10.1007/ s11852-015-0409-5Springer
- Geriesh MH (1989) Hydrogeological investigation of west Ismailia area. MSc thesis, Suez Canal University, Egypt, 120p
- Goswami PK, Pant CC (2008) Tectonic evolution of Duns in Kumaun Sub-Himalaya, India: a remote sensing and GIS-based study. Int J Remote Sens 29(16):4721–4734. https://doi.org/10.1080/01431160802032879
- Guardiani C, Soranzo E, Wu W (2022) Time-dependent reliability analysis of unsaturated slopes under rapid drawdown with intelligent surrogate models. Acta Geotech 17:1071–1096
- Gudmundsson A, Berg SS, Lyslo KB, Skurtveit E (2001) Fracture networks and fluid transport in active fault zones. J Struct Geol 23(2–3):343–353. https://doi.org/10.1016/S0191-8141(00)00100-0
- Hagag W, Obermeyer H (2016) RETRACTED: Rift-related active fault-system and a direction of maximum horizontal stress in the Cairo-Suez district, northeastern Egypt: a new approach from EMR-Technique and Cerescope data. J Afr Earth Sci 121:136–153. https://doi.org/10.1016/j.jafre arsci.2016.06.005
- Haque S, Kannaujiya S, Kumar A, Keshri D, Bhunia R, Ray P, Chauhan P (2020) Identification of groundwater resource zone in the active tectonic region of Himalaya through earth observatory techniques. Groundw Sustain Develop 10:100337. https://doi.org/10.1016/j.gsd.2020.100337
- Hegazi AM, El-Rayes AE, Arnous MO et al (2023) Revealing the geomorphic parameters of neotectonics based on geological and seismic data at Wadi Beda basin, NW Gulf of Suez. Egypt Arab J Geosci 16:82. https:// doi.org/10.1007/s12517-022-11165-4
- Hegazi AM and Omran MA (1998) Structural analysis of Shabrawet area, Northeastern desert, Egypt. GAW4 International Conference on Geol of the Arab World, Cairo Univ, Egypt 91–106
- Henaish A, El Shinawi A, Awad M (2023) Internal architecture and structural evolution of a horst relay zone from the northern Gulf of Suez rift, Egypt: implications for syn-rift sedimentation. Mar Petrol Geol 150:106170. https://doi.org/10.1016/j.marpetgeo.2023.106170

- Hume WF (1925) The Geology of Egypt. V. (I): The surface features of Egypt: Their determining causes and relation to geologic structure. Geol Surv of Egypt, Government Press
- Hussein SM (2001) Hydrogeological and geophysical studies for evaluation of groundwater potentialities at Cairo-Belbeis district, Egypt. PhD thesis, Suez Canal Univ, Fac of Sci, Geol Dept, Ismailia, Egypt 235p
- Kaplay RD et al (2017) Morphotectonic expression of geological structures in the eastern part of the South east Deccan volcanic province (around Nanded, Maharashtra, India). Geol Soc, London 445(1):317. https://doi. org/10.1144/SP445.12
- Kavidha R, Elangovan K (2013) Delineation of groundwater prospective zones by electrical resistivity method in Erode district, Tamil Nadu India. J Environ 20(1):14
- Kebede H, Alemu A, Nedaw D, Fisseha S (2021) Depth estimates of anomalous subsurface sources using 2D/3D modeling of potential field data: implications for groundwater dynamics in the Ziway–Shala lakes basin Central Main Ethiopian Rift. Heliyon 7(4):e06843. https://doi.org/10. 1016/j.heliyon.2021.e06843
- Khali MH (2018) Subsurface faults detection based on magnetic anomalies investigation: a field example at Taba protectorate, South Sinai. J Appl Geophys 131:123–132. https://doi.org/10.1016/j.jappgeo.2016.06.001
- Khalil MH (2016) Subsurface faults detection based on magnetic anomalies investigation: A field example at Taba protectorate, South Sinai, Journal of Applied Geophysics 131:123-132. https://doi.org/10.1016/j.jappgeo. 2016.06.001
- Kolandhavel P, Ramamoorthy S (2019) Investigation of groundwater potential zones in NandiAru sub basin, Tamil Nadu, India—An integrated geophysical and geoinformatics approach. Arab J Geosci. https://doi.org/ 10.1007/s12517-019-4247-x
- Liao K, Wu Y, Miao F, Li L, Xue Y (2021) Time-varying reliability analysis of Majiagou landslide based on weakening of hydro-fluctuation belt under wetting-drying cycles. Landslides 18(1):267–280. https://doi.org/10. 1007/s10346-020-01496-2
- López DL, Smith L (1996) Fluid flow in fault zones: analysis of the interplay of convective circulation and topographically driven groundwater flow. Water Resour Res. https://doi.org/10.1029/96WR02101
- Metternicht Gl, Zinck JA (2003) Remote sensing of soil salinity: potentials and constraints. Remote Sens Environ 85(1):1–20. https://doi.org/10.1016/ S0034-4257(02)00188-8
- Miao F, Wu Y, Li L, Tang H, Xiong F (2020) Weakening laws of slip zone soils during wetting–drying cycles based on fractal theory: a case study in the three gorges reservoir (China). Acta Geotech 15(7):1909–1923
- Moore JP, Walsh JJ (2021) Quantitative analysis of Cenozoic faults and fractures and their impact on groundwater flow in the bedrock aquifers of Ireland. Hydrogeol J 29:2613–2632. https://doi.org/10.1007/s10040-021-02395-z
- Moubarak AH, Arnous MO, El-Rayes AE (2021) Integrated geoenvironmental and geotechnical risk assessment of east port said region, Egypt for regional development. Geotech Geol Eng 39:1497–1520. https://doi. org/10.1007/s10706-020-01571-4
- Moussa H (1988) Earthquake activities in Egypt and adjacent region and its relation to geotectonic features in A. R. Egypt. MSc Thesis, Fac Sci, Mansoura Univ, Egypt 190p
- Moustafa AR, Abd-allah A (1991) Structural setting of the central part of Cairo-Suez district. MERC, Ain Shams Univ, Earth Sc Ser 5:133–145
- Moustafa AR, Khalil MH (1994) Tectonic framework of the northeast Egypt and its bearing on hydrocarbon exploration. 12th EGPC. Expl and Prod Conf Cairo 1:67–86
- Moustafa AR, El Badrawy R, Gibali H (1998) Pervasive E-ENE oriented faults in northern Egypt and their effect on the development and inversion of prolific sedimentary basins. In: 14th Petrol Conference EGPC, Cairo 1: 51-67
- Nabighian MN (1972) The analytic signal of two-dimensional magnetic bodies with polygonal cross-section: its properties and use for automated anomaly interpretation. Geophysics 37(3):507–517
- NASA (1998) Ada style guide. Version 1.1, SEL-87–002. Greenbelt, Maryland: NASA, Goddard space flight center
- NASA (2003) The band designations for the Landsat satellites, http://landsat. usgs.gov/using_Landsat_7_data.php
- NASA (2013) The band designations for the Landsat satellites, http://landsat. usgs.gov/band_designations_landsat_satellites.php

- Newell AJ, Tverdokhlebov VP, Benton MJ (1999) Interplay of tectonics and climate on a transverse fluvial system, upper permian, Southern Uralian Foreland Basin. Rus Sediment Geol 127(1–2):11–29. https://doi.org/10. 1016/S0037-0738(99)00009-3
- Omran AF, Fahmida K, Schröder D, Arnous MO, El-Rayes AE, Hochschild V (2021) GIS-based rockfall hazard zones modeling along the coastal Gulf of Aqaba Region. Egypt Earth Sci Inform 14:691–709. https://doi.org/10. 1007/s12145-021-00580-y
- Panda B, Chidambaram S, Ganesh N (2017) An attempt to understand the subsurface variation along the mountain front and riparian region through geophysics technique in South India. Model Earth Syst Environ. https:// doi.org/10.1007/s40808-017-0334-8
- Phillips JD (2002) Processing and interpretation of aeromagnetic data for the Santa Cruz Basin--Patagonia Mountains Area, South-central Arizona. US Department of the interior, US geological survey.
- Ramadan FS (1984) Sedimentological studies on the bottom sediment of the Suez Canal. MSc Thesis, Zagazig Univ, Egypt 128p
- Rao B, Silpa S (2023) A review of geophysical research: perspective into the Indian ocean geoid low. Earth-Sci Rev 237:104309. https://doi.org/10. 1016/j.earscirev.2022.104309
- Rawat PK, Tiwari PC, Pant CC (2011) Climate change accelerating hydrological hazards and risks in Himalaya: a case study through remote sensing and GIS modeling. Int J Geomatics Geosci 1:678–699
- RIGWA (1988) Hydrogeological map of Egypt scale (1:2,000,000), 1st edition, Res. Inst. for Groundwater, Water Research Center, Ministry of Pub Work and Water Reso, Egypt
- Rubio JC, Simón JL, Soriano MA (2007) Interacting tectonics, hydrogeology and karst processes in an intramontane basin: the Jiloca Graben (NE Spain). Hydrogeol J 15:565–576
- Saada SA, Mickus K, Eldosouky AM, Ibrahim A (2021) Insights on the tectonic styles of the red sea rift using gravity and magnetic data. Mar Petrol Geol 133:105253. https://doi.org/10.1016/j.marpetgeo.2021.105253
- Sadek R (1926) The geography and geology of the district between Gabal Ataqa and El-Galala El-Bahariya (Gulf of Suez): Egypt Surv Dept, Cairo 120p
- Sallam E, Issawi B, Osman R (2015) Stratigraphy, facies, and depositional environments of the Paleogene sediments in Cairo-Suez district. Egypt Arab J Geosci 8:1939–1964. https://doi.org/10.1007/s12517-014-1360-8
- Shata AA, El-Fayoumy LF (1970) Remarks on the hydrogeology of the Nile Delta. Sym. of hydrology of the Nile Delta. UNESCO 2:385–396
- Singh A (2022) Soil salinity: a global threat to sustainable development. Soil Use Manag 38:39–67. https://doi.org/10.1111/sum.12772
- Spector A, Grant FS (1970) Statistical models for interpreting aeromagnetic data. Geophysics 35:293–302. https://doi.org/10.1190/1.1440092
- Spottke I, Zechner E, Huggenberger P (2005) The southeastern border of the upper rhine graben: a 3D geological model and its importance for tectonics and groundwater flow. Int J Earth Sci 94:580–593. https://doi.org/10.1007/s00531-005-0501-4
- Srinivasan R, Lalitha M, Chandrakala M, Dharumarajan S, Hegde R (2022) Application of remote sensing and GIS techniques in assessment of salt affected soils for management in large scale soil survey. In: Shit PK, Adhikary PP, Bhunia GS, Sengupta D (eds): Soil health and environmental sustainability. Environmental Science and Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-09270-1_7
- Strougo A, Abd-Allah A (1990) Mokattam stratigraphy of North Eastern Desert (South of Maadi Qattamyia road). MERC, Ain Shams Univ. Earth Sc Res Ser 4:152–175
- Suez Canal University & UNEP (1997) Vulnerability assessment of low-lying coastal areas in the southern part of the Suez Canal, in the context of climate change and sea level rise. Suez Canal Univ, Ismailia, Egypt, Internal Report, Egypt, p 205
- Taylor R, Howard K (2000) A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: evidence from Uganda. Hydrogeol J 8:279–294. https://doi.org/10.1007/s100400000069
- Tschirhart P, Morris B, Hodges G (2013) A new regional/residual separation for magnetic data sets using susceptibility from frequency-domain electromagnetic data. Geophysics 78(6):B351–B359. https://doi.org/10. 1190/geo2012-0506.1
- USGS website: https://earthexplorer.usgs.gov
- Weight WD (2001) Hydrogeology field manual. 2nd Edition, McGraw-Hill Companies, Inc. https://doi.org/10.1036/0071477497

- Youssef M, Abdallah A (2003) Structural geology of the southern part of the Cairo-Suez district, Egypt. 5th Inter. Conf. for the Geology of the Middle East, Cairo, (Abstract)
- Youssef YM, Gemail KS, Sugita M et al (2021) Natural and anthropogenic coastal environmental hazards: an integrated remote sensing gis, and geophysical-based approach. Surv Geophys 42:1109–1141. https://doi. org/10.1007/s10712-021-09660-6
- Zain El-Din MY, Darwish M, Bakry G (1994) Basin development and hydrocarbon potentials of the south Nile Delta provinces, Egypt. In: 2nd international conference on Geological Arab World, Cairo University, Egypt 185–218
- Zhu T, Feng R, Hao J, Zhou J, Wang H, Wang S (2009) The application of electrical resistivity tomography to detecting a buried fault: a case study. J Environ Eng Geophys 14(3):145–151. https://doi.org/10.2113/JEEG14. 3.145
- Zohdy AR (1989) A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. Geophysics 54(2):245–253. https://doi.org/10.1190/1.1442648
- Zohdy AR (1974) Use of Dar Zarrouk curves in the interpretation of vertical electrical sounding data. United States Geol Surv Bull 1313(41):4

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Submit your manuscript to a SpringerOpen[®] journal and benefit from:

- Convenient online submission
- ► Rigorous peer review
- Open access: articles freely available online
- ► High visibility within the field
- Retaining the copyright to your article

Submit your next manuscript at > springeropen.com