Shear Zones Effects on Groundwater Flow in Southern Sinai, Egypt: Remote Sensing and Geophysical Constraints

Lamees Mohamed

Department of Geosciences, Western Michigan University, Kalamazoo, MI

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ABSTRACT
This study presents an integrated analysis and interpretation of Very Low Frequency (VLF) and remote sensing data sets. The study area is located in southern part of the Sinai Peninsula, an area that suffers from severe shortages in fresh water supplies. This is largely related to low precipitation rates (5 to 60 mm/yr) and low permeability of the basement rocks that cover most of the study area. The bedrock is dissected by dikes, faults, and shear zones which play a major role in controlling groundwater flow and accumulation. The fracturing in the basement rocks associated with faulting and brittle shear zones controls the distribution of water bearing aquifers in the basement complex. Understanding the distribution of these structural elements and their cross-cutting relations together with the hydraulic gradient in the area gives clues as to the distribution of the water resources in the area. Field and geophysical investigations were conducted to test the validity of the remotely sensed distribution of water bearing shear zones and faults.

1. Introduction

Demand for freshwater supplies in arid and semi-arid countries worldwide is on the rise because of increasing populations. This problem is exemplified in countries of Saharan Africa (North Africa) and the Middle East, where scarcity of water resources is contributing to political instability, disputes, and conflicts. Egypt is one of the most populous countries in Africa (about 90 millions). Most of the 90 million inhabitants live near the banks of the Nile River and the Nile delta, in an area of about 40,000 km². The Nile River has been a vital surface freshwater resource for Egypt’s population and has been used for the development of its agricultural and industrial sectors. Egypt is considered as one of the hyper-arid countries world-wide. Temperatures in Egypt are high (average mean temperature: 22°C), and rainfall is low (average annual precipitation: 26 mm)(REF). Nowadays, efforts have been directed toward finding renewable water resources to develop new agricultural and industrial communities outside the overpopulated Nile Delta and Nile Valley. Sinai is one of the most promising regions for the development in Egypt because of its strategic location and adequate climatic conditions. Rainfall precipitating over the elevated crystalline rocks at Saint Catherine area represents the main source of groundwater supply. Saint Catherine area is located in south Sinai which includes the highest mountainous peaks in Sinai (2641 m a.m.s.l at Gabal Catherine; Fig.1). Saint Catherine area is characterized by an arid climate with a mean annual rainfall of about 60 mm, though the high peaks receive orographic precipitation, some in the form of snow, which may reach up to 300 mm annually.

Occasional precipitation over the Saint Catharine mountainous area is commonly channeled throughout extensive watersheds as surface runoff in wadis that cross-cutting the mountainous area and as subsurface groundwater flow in wadi fills and fractured weathered portion of the basement rocks. The Saint Catherine area is mainly composed of medium to coarse-grained granites, granodioritic-dioritic association,
monzonites, syenites, Catherine volcanics and Rutig volcanics (Bentor and Eyal, 1969) which are known by their massive nature and low primary permeability. Fractures, faults and shear zones are exceptional factors which increase the permeability and enhance the fluid transport through fractured and sheared rocks (Barton et al., 1995). The rock units are highly affected by several faults and joints with different trends and densities. Such structures govern a widely distributed hydrographic system (Elfouly 2000).

In this study, we develop and apply integrated cost-effective and efficient methodologies to develop a better understanding of the role of different structural elements (e.g., shear zones, faults) in collecting and channeling groundwater. The developed methodologies include Very Low Frequency (VLF) Electromagnetic measurements, temporal water table measurements along with remote sensing data. The later include, but not limited to, (1) Visible Near-Infra Red (VNIR) data, (2) European Remote Sensing Environmental Satellite-Advanced Synthetic Aperture Radar (Envisat-ASAR) radar imagery, and (3) Tropical Rainfall Measuring Mission (TRMM).

One of the foreseen outcomes of this study is to delineate water-bearing sub-vertical shear zones within the basement complex which will assist in locating optimum locations for digging water wells in selected wadis in the study area. The selected wadis will be those that accumulate large amounts of groundwater, the sources of which could be infiltration from runoff and groundwater channeled by structures intersecting the wadis. This dammed water could potentially be used in agriculture, domestic purposes, and industry.

2. Geologic Setting

Saint Catherine complex is located in the highest mountainous area of southern Sinai including parallel ridges separated by deep wadis that have been cut along faults and fractures and enlarged through intense precipitation events during the old pluvial periods. The area was described early by Barron (1907).

The ring complex of Saint Catherine is a major ring structure. It is 28 km in diameter and ranges of width between 1 to 5 Km with the highest peak 2455 m above sea level. The southern part of the ring massif is composed of black volcanic rocks, incorporated as xenoliths in the red alkali rhyolites, and syenites. The northern part of the ring massif consists only of syenite. (Abdel Maksoud et al., 1993)

Saint Catherine area represents the highland of Wadi Feiran drainage basin which extends downward from the peaks of the crystalline basement rocks to the low laying sedimentary rocks at the coastal plain of the Gulf of Suez (Issar and Gat, 1981). Wadi Feiran Basin includes four water bearing formations; the Quaternary alluvium, Miocene-Post Miocene sandstone, Lower Cretaceous sandstone and fractured basement rocks (Aggour, 2005). Catherine volcanics and the surrounding granitic rocks in Saint Catherine area, which are generally impermeable except through fractures such as faults, joints and shear zones (Shendi and Abouelmagd, 2004), are recharged with average 50 mm annual precipitation (Abouelmagd, 2003). Surface runoff (about 14 million m³, Elewa and Qaddah, 2011) is lost through flooding that attacks the Feiran- Catherine road (Youssef et al, 2011) and may moisten only the upper part (less than ten meters) of the wadi fill (Wachs et al, 1979). A net groundwater recharge of about 11 million m³ (Elewa and Qaddah, 2011) find their way through sets of interconnected joints to feed the existing wells in the low-lying fault zones (El-Rayes, 2004) and also discharged as springs along the contact between the weathered, fractured topmost rocks and the underlying fresh granites (El-Rayes, 1992). In this manner, groundwater moves in a step-like downward flow until the fault zone is reached (El-Rayes, 2004). These jointed and fractured rocks are dissected by NE-SW dikes, which play an important role in the groundwater occurrences in the fractured basement rocks and alluvium deposits (Aggour, 2005).

3. Climate and hydrologic setting

Saint Catherine area is characterized by its mild climate compared to the surrounding arid area. Temperature ranges from 23 to 32°C in summer and from 9 to 12°C in winter (JICA, 1999).
Fig. 1. A) Location map showing the study area. B) Geologic map showing the distribution of the outcrops in the study area modified after, Elfouly 2000 and the geological Atlas of Sinai, 2002
The precipitation is mostly of orographic type due to forcing moist air masses to higher altitudes and the condensation of their moisture either as snow or as rainfalls in the form of flash floods (El-Shamy et al., 1989). A precipitation event was recorded in 17 and 18 January 2010 from the TRMM images and records of the ground gauge stations (Nekhel station) over Saint Catherine (Fig. 2).

Hydrological settings within the major mountainous ranges of the world are characterized by the occurrence of fractured rock aquifers. As opposed to porous aquifers, which store and transmit water through pore spaces between individual sediment granules, fractured rock aquifers store and transmit water through crevices, joints and fractures in otherwise impervious rocks. The occurrence and flow of groundwater that occurs in these types of aquifers is controlled by spacing, aperture size, orientation and connectivity of permeable preferential pathways that occur within discontinuities.

Types of discontinuities that facilitate groundwater flow include joints and other fractures, foliation, faults, shear zones, geologic contacts and bedding planes. Some structures as dikes and faults may also act as barriers to groundwater flow. In many fractured rock settings the watershed or surface drainage basin can be an appropriate, natural unit within which to characterize and manage surface water and groundwater resources. The development of widespread shear zones and fracture systems has generated considerable secondary porosity (fracture porosity) within the study area. From a hydrogeological point of view, faults and shear zones constitute very important types of discontinuities in rocks, and in the same time shear zones tend to be more extensive and continuous than joints (Fig. 3, Singhal and Gupta 2010).

In such hydrogeological systems the velocity of groundwater flow is generally much higher than in porous media, although yields are mostly low due to limited groundwater volumes and sporadic recharge events. The Arc Hydro tool of ArcGIS 10 has been used to create a basis for obtaining a deeper understanding of the drainage and watershed system in the studied area (Fig. 4). Flow direction was estimated using the Arc Hydro Groundwater tool provided by AQUAVEO (Water Modeling Solutions). The Surface drainage network pattern (surface runoff features) was found that it coincides with the pattern of the groundwater flow direction in the fractured basement rocks and Quaternary alluvium. So, the effect of faults and dams on the ground water flow in the study area may be indicated by their effect on the surface runoff.

Water levels in eighteen wells were used to draw the potentiometric surface map in the study area using the ordinary kriging method of interpolation (The best interpolation method choose after the cross validation technique (Fig. 5).

4. Integrated Methodology
   a. Remote sensing data set for lithological mapping

The band ratio image (5/7, 5/1, 5/4 * 3/4) in RGB that has been provided by Sultan et al., (1987) to differentiate between serpentinites and metavolcanics in Meatiq Dome and Wadi Ghadir areas in Egypt, was applied on a Landsat 8 image covering the study area. Depending on the variation of the spectral reflectance of the different rock types (Sabins, 1997), the ratio image (Fig. 6) is capable of differentiating 11 lithologic units. The results were correlated with the detailed lithological descriptions of El-Masry et al., (1992) in order to identify the lithological correspondence of each color tone. The highly sheared area around Saint Catherine Monastery is entirely composed of alkali granites and the differential weathering across it is probably a tectonic response.
A) Location map of the Nekhel Station in Sinai, Egypt. B) Accumulated precipitation from TRMM 3B42RT.v6 acquired (17-18 Jan, 2010) over southern Sinai showing the highest precipitation in Saint Catherine area.

Fig. 3. Schematic presentation of the conceptual model of groundwater flow based on the proposed effects of the intersections of faults and shear zones in the studied area. (modified after Babiker and Gudmundsson, 2004)
Fig. 4. DEM derived watershed and stream networks in Saint Catherine area.

Fig. 5. Regional groundwater flow
b. Remote sensing datasets for structural analysis

Primary information about the orientation, distribution and extension of the major structural elements in Saint Catherine area was obtained from the integration of the hill shade, SIR-C and Landsat 8 images (Fig. 7) and finally this data was compiled with the Geological Atlas of Sinai (AT-TUR map 1:250,000, Fig. 8), high spatial resolution images (Google Earth, Fig. 9) and field investigation (Fig. 10) with previous work. The major structural features include; shears and faults.

c. Radar-ENVISAT Advanced Synthetic Aperture Radar (ASAR)

The complex dielectric constant is a measure of the electric properties of surface materials. It consists of two parts (permittivity and conductivity) that are both highly dependent on the moisture content of the material considered. In the microwave region, most natural materials have a dielectric constant between 3 and 8 in dry conditions.

Water has a high dielectric constant (80) at least 10 times higher than for dry soil. As a result, a change in moisture content generally provokes a significant change in the dielectric properties of natural materials; increasing moisture is associated with an increased radar reflectivity. (Wang et al., 2004).

Advanced Synthetic Aperture Radar (ASAR) is operating at C-band, ensures continuity of data after ERS-2. Its features enhanced capability in terms of coverage, range of incidence angles, polarization, and modes of operation. The improvements allow radar beam elevation steerage and the selection of different swaths, 100 or 400 km wide. The pixel value in the image is proportional to the square root of the intensity, which in the same time depending on the radar brightness $\beta_0$. The radar brightness $\beta_0$ is proportional to the backscattering coefficient $\sigma_0$ divided by the sine of the pixel incidence angle. ASAR calibrated image provides an imagery in which the pixel values can be directly related to the radar backscatter of the scene.

Two ENVISAT ASAR images were examined to identify changes in radar backscatter that is controlled by changes in soil moisture content following precipitation events. We expect that certain structures will provide preferential conditions for the accumulation of groundwater that could be readily detected from temporal variations in soil moisture to be extracted from radar imagery. One main precipitation event was selected in 17 and 18 January 2010. A color composite image was generated using two ASAR scenes; one before the rain event in 11 November 2009 and the other one after the rain event in 20 January 2010 (Fig. 11).

The composite image shows that following the precipitation event, water bearing faults and shear zones show higher moisture content than their surroundings and this is represented by the red colors along the shear zones and the sheared rocks (Fig. 11). The sheared rocks are highly permeable regardless of the occurrence of faults but the permeability is supposed to decrease suddenly when the sheared rocks are intercepted by faults perpendicular to shear zones.
Legend

1) Wadi deposits
2) Prophyritic, equigranular dike-like intrusion
3) Metadiorite
4) Metagabbro
5) Coarse to medium-grained alkali granite
6) Porphyritic quartz syenite
7) Coarse to medium-grained mozonite
8) Coarse to medium-grained olivine hornblende gabbro
9) Coarse to medium-grained foliated monzogranite
10) Araba Formation
11) Mafic dike

Fig. 6. Ratio image (5/7, 5/1, 5/4 * 3/4) in RGB over the studied area with an interpretation of the Lithology distribution.

Fig. 7. The data base layers: a) PC image, b) Hill shade image, c) SIR-c, d) Ratio image.
Fig. 8. Geologic map of At Tur (southern Sinai), UNESCO 2002.

Fig. 9. High spatial resolution images (Google Earth) of one of the shear zones.

Fig. 10. Field photos of some faults and shear zones in the study area.

Fig. 11. a) Composite ENVISTA ASAR image for the shear zones in the studied area, b) High resolution Google Earth image of the same area.
**Frequency method (VLF)**

VLF method is an effective method in detecting conductive water saturated and sub-vertical breccia zones in bedrock (Palacky et al., 1981). Eleven sites were visited over a period of four days, and a total of thirty four VLF transects were surveyed in the horizontal profiling mode along transects ranging from 220 to 940 m with station spacing of 10 and 20 m.

VLF profiles were conducted along transects in Saint Catherine area (VLF 1- VLF 7) (Fig.12). The wadi of Saint Catherine Monastery is NW-SE trending wadi that cross-cut the basement complex. The wadi intersects two sets of NE-SW, and NW-SE shear zones that cutting the alkali granite and the coarse-moderate grained monazite. VLF profile-1 was conducted along the beginning of the wadi cross-cutting the NE-SE shear zones. VLF anomalies were observed along the postulated extension of the shear zones in the main valley where tilts of up to 60% were observed (Fig.13a). Additional VLF profile was conducted in the middle of the wadi (VLF-2) cross-cutting the NW-SE shear zones. Two large anomalies (tilt: >50%; Fig.13b) were observed at the postulated extension of the shear zones into the wadi. Vegetation areas were found along two of the shear zones, supporting the VLF based suggestion that groundwater is descending along the shear zones.

The VLF tilt anomalies (40%) were observed along the traverse (VLF-3) that was conducted along the end of the wadi. These anomalies also indicate the locations of descending groundwater along the shear zones (Fig.13c).

At the intersection of the NW-SE and NE-SW trending shear zones (>30%) Vlf tilt anomaly was observed (Fig. 13e). In summary, we interpret the observed spatial correlation of the VLF anomalies with the location of major NW-SE or NE-SW trending shears in the examined locations as indicative of groundwater flow along major shears that affected the area. We defined areas of shear zone (tens to hundreds of meters) that show high groundwater potential by using Radar images. These areas were visited to collect field observations and VLF data in order to identify potential locations within the study area. The initial selection which is based on Radar images was verified when the shear zones were identified in the field and one or more Fraser Filtered tilt anomalies (>20% tilt) were observed.

![Fig.12. Distribution map of the shears and VLF profiles](image-url)
Fig. 13. VLF transects at the intersection of shear zones with high resolution Google Earth image shows the locations of the transects.
6. Summary

We integrated different methods as field geology, geophysics, remote sensing and cost effective GIS technologies for investigating groundwater potential locations that associated with major shear zones in the study area. To demonstrate that shear zones generate a net system for hosting and transmitting groundwater we followed these main steps: 1) the shear zones within the basement complex were delineated using false color images that were generated from Landsat-8 Thematic Mapper (ETM) band, high spatial 1 m resolution Orb-view3 image, Google Earth images, hill shade and band ratio images; 2) the spatial and temporal precipitation events over the basement complex were then identified from TRMM data; 3) observations extracted from temporal change in backscattering values in radar (Envisat ASAR radar scenes) were used to identify the water-bearing shear zones and (4) finally, field observations and VLF investigations were then applied to test the validity of our satellite-based methodologies for locating targeted aquifer types and for refining the satellite-based selections.

Many wells in Saint Catherine area were found along the shear zones especially at the intersection of two or more shear zones or at the intersection of shear zone and fault system. The area is generally affected by two main sets of shears; NNW-SSE and NE-SW. Groundwater in Saint Catherine area exists in both the sheared basement rocks and the Quaternary alluvial deposits. VLF transects were tested in eleven sites for detailed detection of the groundwater potential areas. Six sites showed Fraser Filter tilt values >30%, indicating the presence of shallow subvertical electrical conductor within the subsurface. VLF tool was useful to refine the scale (10-100s m) of Radar images based selection to the fracture scale. The integration of Radar images with field and geophysical observations to identify the groundwater potential locations is important to overcome the uncertainty of using Radar images alone. Our technique is successful to clarify the role of shear zones in hosting and transmitting groundwater in the study area. It is worthy to apply in other arid area of the world. For this study, it is recommended that more geophysical field work (more VLF profiles, GPR profiles to map the saturated interface) to be applied before deciding to drill new wells.

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