Structural Controls on the Distribution of Groundwater in Southern Sinai, Egypt: Constraints from Geophysical and Remote Sensing Observations

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STRUCTURAL CONTROLS ON THE DISTRIBUTION OF GROUNDWATER IN SOUTHERN SINAI, EGYPT: CONSTRAINTS FROM GEOPHYSICAL AND REMOTE SENSING OBSERVATIONS

by

Lamees Mohamed

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy Geosciences Western Michigan University May 2015

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An integrated (Very Low Frequency [VLF] electromagnetic, magnetic, remote sensing, field, and Geographic Information System [GIS]) study was conducted over the basement complex in Southern Sinai (Feiran watershed) for a better understanding of the structural controls on the groundwater flow. The increase in satellite-based radar backscattering values following a large precipitation event (date: 17, 18 Jan 2010; amount: 34 mm) was used to identify water-bearing features, here interpreted as preferred pathways for surface water infiltration. Findings include: (1) The distribution of the water bearing features (conductive features) correspond to that of fractures, faults, shear zones, dike swarms, and wadi networks; (2) About 85% of the investigated conductive features were determined to be preferred pathways for groundwater flow; (3) NW-SE to N-S trending conductive features that intersect the groundwater flow (SE to NW) at low angles, capture groundwater flow; (4) NE-SW to E-W features, that intersect the flow at high angles impound groundwater upstream and could provide potential productive well
locations. Similar findings are observed in Central Sinai: E-W trending dextral shear zones (Themed and Sinai Hinge Belt) impede S to N groundwater flow as evidenced by the significant drop in hydraulic head (from 467 to 248 m a.m.s.l) across shear zones and by reorientation of regional flow (S to N to SW to NE). The adopted integrated methodologies could be readily applied to similar highly fractured basement arid terrains elsewhere.
“Yet, in spite of this, your hearts only hardened like rocks or even harder, but among rocks are those from which rivers flow; and there are also those which split open and water gushes forth; as well as those that roll down for fear of God. And God is not negligent of all that you do.”

(Holy Qur'an, 2:74)

To my parents and my daughters who have supported me in many ways along this journey.
To my sisters and my friends in Egypt and USA you were always with me.
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In the Name of Allah, the Most Gracious, the Most Merciful

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

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. 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 km$^2$. Egypt heavily relies on (1) allochtonous precipitation over the Ethiopian highlands and Equatorial Africa that is channeled to the downstream by the River Nile, and (2) autochthonous precipitation that recharged its fossil aquifers (e.g., Nubian Sandstone Aquifer System [NSAS]) during previous wet climatic periods (Sultan et al., 1997; Thorweihe, 1982). 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. However, Egypt is currently using its total annual allocation of River Nile water, estimated at $55 \times 10^9$ m$^3$/yr. It is considered as one of the hyper-arid countries world-wide as it experiences from high temperatures (average mean temperature: 22°C), and low rainfall (average annual precipitation: 26 mm). Recently, 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. The corner stone for any development is the availability of water resources. Rainfall precipitating over the elevated crystalline rocks in the Saint Catherine area represents the main source of groundwater supply. The Saint Catherine’s area is located in southern Sinai where the highest mountainous peaks are located (2641 m a.m.s.l at Gabal Catherine; Fig.1). This area is mostly characterized by an arid climate with a mean annual rainfall of about 60 mm, however the high peaks receive orographic precipitation, some in the form of snow; and the precipitation (rain or snow) 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 crosscut the mountainous areas and as subsurface groundwater flow in wadi fills and in fractured basement rocks. This area is mainly composed of medium to coarse-grained granites, granodioritic-dioritic association, monzonites, syenites, Catherine volcanics and Rutig volcanics (Bentor and Eyal, 1969); these rock units are identified by their massive nature and by their low primary permeabilities. The presence of fractures, faults and shear zones increase the permeability and enhances the fluid transport through fractured and sheared igneous and metamorphic rocks (Barton et al., 1995, Caine et al., 1996, Evans et al., 1997 and Gudmundsson et al., 2001). The rock units in the study area are highly affected by
several faults and joints with different trends and densities. Such structures govern the
distribution of groundwater over extensive areas in southern Sinai (Elfouly, 2000).

One of the favorable areas for hosting groundwater is an area where a number of
faults, fractures, or shear zones intersect. Shear zones are wide zones (width: tens of
meters to kilometers) of distributed and intense deformation, while faults accommodate
deformation along distinct fault planes. The intersection of faults and shear zones
enhances porosity and provides the conditions for hosting groundwater within the
basement rocks (Blenkinsop and Kadzviti, 2006; Goddard and Evans, 1995). The soil
water content, especially at or near the surface, is a key parameter in determining the
partitioning of the water flow on the land surface into the different compartments (ground
water storage, surface runoff, evapotranspiration, and soil-moisture storage (Le Hégarat-
Mascle, et al., 2002). The sensitivity of radar backscatter to surface soil moisture
conditions (via the change of the soil dielectric permittivity) has led to a considerable
interest in exploiting data collected by space-borne radar imaging satellites, such as
Envisat, for the retrieval of soil moisture information. (Quesney, et al., 2000)

In this study, I 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
methodologies include Very Low Frequency (VLF) electromagnetic measurements and
temporal water table measurements along with remote sensing data.
Figure 1: Map showing the distribution of Precambrian outcrops and overlying Phanerozoic rock units in Sinai, Feiran watershed (red polygon), hydraulic head data (blue lines) and regional groundwater flow (black arrows) for the NSAS in Central Sinai extracted from 25 wells (green circles; Rosenthal et al. 2007), and three main shear zones (purple lines) (Bosworth and McClay, 2001; Moustafa et al., 2013). Inset shows the regional distribution of the Arabian Nubian Shield outcrops.
Figure 2: TRMM and VLF data over the study area; (a) Average annual precipitation extracted from TRMM 3B42.v7A 3-hourly data acquired (1998–2013) over Egypt and surrounding countries. (b) Locations of VLF and magnetic profiles acquired in 2011, 2012 and 2013 (area outlined by white box in figure 1).
The remote sensing data include, but are 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 purposes of this study is to delineate water-bearing structures within the basement complex, to assist in locating water wells in selected wadis. The selected wadies are those that accumulate large amounts of groundwater, the sources of which could be infiltration from runoff and groundwater channeled by structures intersecting the wadies. The identified optimum locations could be potentially used for agriculture, light industry or domestic purposes.

1.2 Research Objectives

The main objective of this study is to locate and assess potential renewable groundwater resources in Sinai. Given the structural complexities in Sinai, this will largely depend on developing an understanding of the role of different structural elements (e.g., shear zones, faults) in collecting and channeling groundwater. This objective will be achieved by:

(1) Delineating the distribution of structures in the study area and developing an understanding their control on groundwater flow.

(2) Developing and applying integrated (geophysics, remote sensing, GIS, field) cost-effective methodologies for a better understanding of the spatial distribution and role of structural elements (e.g., shear zones, faults) in collecting and channeling groundwater in
southern Sinai, Egypt. This approach involves the use of remote sensing data to delineate structural elements in the study area, identify the structures that are water-bearing, and test the validity of the satellite-based observations using geophysical and field data.

1.3 Study Area

Sinai is one of the most promising regions for the development of alternative water resources given the relatively high amount of precipitation. Examination of the 3-hourly precipitation data from the Tropical Rainfall Measuring Mission (TRMM; 1998 to 2012; 3B42v7A; discussed below) show that, the average annual precipitation (AAR) over the Western Desert, Eastern Desert, and Sinai is 9 mm, 13 mm, and 70 mm, respectively (Fig. 2a). Rainfall over the mountainous basement complex in southern Sinai is channeled as surface runoff into wadi networks and as subsurface groundwater flow in wadi fills and fractured basement rocks. Favorable settings for hosting and channeling groundwater within the basement complex include areas of enhanced porosity where faults, fractures, or shear zones intersect (Blenkinsop and Kadzviti, 2006; Goddard and Evans, 1995; Sultan et al., 2008).

1.4 Climatic Setting

Wadi Feiran 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). The area is characterized by precipitation of mostly orographic type due to forcing moist air masses to higher altitudes and the condensation of their moisture either
as snow or as rainfall in the form of flash floods. The relative humidity ranges from 30% to 60% and reaches up to 90% during rainy periods (El-Shamy et al., 1989).

1.5 Previous Studies

Studies that addressed the evaluation of the impact of the structural elements on groundwater flow patterns are few and such investigations remain a challenge to researchers, as it requires an integration of structural and hydrogeologic research efforts.

Issar and Gilad (1982) investigated three main flow systems in Southern Sinai; the flow system existing along the crustal fractures which are parallel to the Gulf of Elat Rift; the flow system in shallow fractured rocks which capturing, and the system of dikes which govern the flow regime in wadi beds. Li (1994) found that fractures in granitic rocks which are a product of tensional forces, often contained more water than those formed by compressional forces. His explanation was that tensional fractures are wide, compared to compressional fractures. Moreover, tensional forces often give rise to echelon fractures, a process that provides yet another reason for more ground water to be found within tensional fractures.

Caine and others (1996) mentioned that many brittle fault zones contain a narrow core of fine-grained, relatively low-permeability gouge that is the locus of fault displacement. The fault core zone could be flanked by a damage zone, a zone characterized by networks of subsidiary small faults and fractures that enhance secondary permeability (Caine and others, 1996; Caine and Forster, 1999). In many cases, the core zone reduces permeability relative to that of the original rock or the surrounding damage
zone as a result of progressive grain-size reduction, formation of clay minerals, and mineral precipitation during fault motion. Low-permeability fault cores potentially restrict fluid flow across the fault, whereas the damage zone may conduct groundwater flow parallel to the fault zone (Sweetkind and others, 2010).

Hurlow (2004) stated that the fault core, when perpendicular to groundwater flow, forms a barrier to the flow across its plane. Fractures can behave as impermeable barriers to flow by preventing the movement of aquifer fluids across the fracture zone and by channeling the fluids along the zone parallel to the trend of the fractures (El Fouly, 2000).

Babiker and Gudmundsson (2004) mentioned that minor fractures contribute to the permeability associated with dikes, faults and their intersections in the Red Sea Hills region of the Sudan. In addition, the minor fractures contribute to groundwater storage in that area. This effect of the faults on the groundwater flow depends on fault trend in relation to the hydraulic gradient and the steepness of the slope. Becker and Sultan (2007) reported that modern groundwater which originated from sporadic precipitation over the mountainous areas in southern Sinai, was channeled as surface runoff throughout watersheds, and as groundwater flow in underlying alluvial aquifers. A part of this precipitation ends up in the underlying fractured basement complex, in dyke-related reservoirs and fractured Eocene limestone.
CHAPTER 2

GEOLOGY AND HYDROGEOLOGY

South Sinai is bounded to the east by the Gulf of Aqaba and to the west by the Gulf of Suez. This area is a part of the Sinai Peninsula (total area of Sinai is 61,000 km\(^2\)). The Sinai Peninsula is part of the great arid belt of North Africa and Southwest Asia. This chapter sheds light on the geologic, structural and hydrogeologic setting of the studied area within south Sinai.

2.1 Geologic and Structural Setting

The exposed Proterozoic crystalline rocks in the South Sinai Peninsula (Fig. 1) together with those in the northern Eastern Desert of Egypt represent the northwestern extension of the Arabian–Nubian Shield (ANS; inset Fig. 1). The earlier phases (950-650 Ma) of evolution of the ANS in Sinai involved the accretion of island arcs and closure of interleaving oceanic basins that gave way to an intraplate extensional phase of deformation. The ANS terrain transitioned into a stable cratonic phase by 450 Ma (Garfunkle 1999). The extensional phase was characterized by bimodal mafic (basalt and basaltic andesite) and felsic (dacite, rhyodacite, rhyolite) dike swarms (Stern et al. 1984, 1988; Eyal and Eyal 1987; Friz-Topfer 1991). Approximately 70% of the Southern Sinai is outcrop. The main rock units encountered are syn- and post-orogenic granitoids, meta-
volcanics, meta-sediments, and gneissic and migmatitic rocks of various compositions (Fig. 1) (Shimron 1973; Eyal 1975; Bartov et al. 1979; Issar and Gilad 1982).

The complex and prolonged tectono-magmatic history of the southern Sinai gave rise to generations and modes of magmatic and volcanic activity and a wide range of structural elements and styles of deformation. The study area is highly dissected by brittle faults and shear zones; the most prominent of these systems are NW-trending sinistral faults and shear zones that are dissected by NE-trending dextral faults and shear zones.

The sinistral faults are here interpreted to be post-accretionary Najd faults of late Precambrian age. The Najd shear zone extends over 1200 km in a NW-SE direction in the Arabian Shield, with an average width of ~300 km (Agar 1987) and aligns with faults in the South Yemen coast (Brown and Coleman 1972), making a potential total length in excess of 2000 km (Moore 1979).

Using a pre–Red Sea rift reconstruction, together with field, geochemical, and geochronological data, Sultan et al. (1988, 1992, 1993) mapped the extension of the Najd shear system of the Arabian Shield into the Central Eastern Desert of Egypt, bringing the total length of the Najd system in the ANS to 2300 km (Fig. 3). Along the zone occupied by the Najd system in the ANS, both brittle and ductile styles of deformation are superimposed on, and obliterate earlier accretionary tectonic features (Sultan et al. 1988). A major NW-trending Najd shear zone (Rihba shear zone: length 50 km; width 200 m; Fig. 1) extends into the study area (Mostafa 1997; Bosworth and McClay 2001; Younes and McClay 2002; Sultan et al. 2012).
Figure 3: Simplified map showing the Najd shear system trend. (modified after Johnson et al., 2013)

The origin of the NE-trending dextral fault set is less constrained. It may be conjugate to the main NW-trending Najd shear system as commonly observed in the ANS (Moore 1979; Greiling et al. 1994; Johnson and Woldehaimanot 2003; Shalaby 2010). Alternatively, the dextral fault set could be much younger in age. The sinistral slip
(post-Early Miocene to Recent) on the Dead Sea Transform and associated drag on the eastern edges of preexisting E-W to ENE-WSW oriented faults could have resulted in simple dextral wrenching (Mostafa and Khalil 1994). Also, a transtensional origin for these dextral faults was proposed, where the throw along the Gulf of Suez rift-related NW-SE oriented faults could have caused Late Oligocene to Early Miocene divergent dextral wrenching along pre-existing faults (Mostafa and Khalil 1994; Mostafa 1997; Younes and McClay 2002).

The basement complex in the study area is formed of a series of rocks generally with complex structure beneath the dominantly sedimentary rocks. These are igneous and metamorphic rocks of either Early or Late Precambrian, but in some places, these may be much younger, asPaleozoic, Mesozoic, or even Cenozoic. Southern Sinai is dissected by numerous vertical to sub-vertical dike swarms (length: 0.1 to 15 km; width: 0.5 to 20 m) of mafic, intermediate and felsic compositions (Stern et al. 1988; Lacumin et al. 1998). Dike swarms in the study area are classified in three main groups based on their age of emplacement: 1) metamorphosed syn-tectonic dikes (age: 800-650 Ma; Eyal and Eyal, 1987); 2) widely distributed, unmetamorphosed, post-orogenic dikes (591-459 Ma) of extensional, late Pan-African origin (Stern et al. 1984; Stern and Hedge 1984; Lacumin et al. 1998); and 3) Neogene dikes (30-12 Ma) related to the extensional forces associated with the Red Sea Rift system (Meneisy 1990). The first two groups are mafic, intermediate, and felsic in composition, whereas the Neogene dikes have basaltic compositions (El-Sayed 2006).
2.2 Hydrogeologic Setting

Precipitation in the study area is largely controlled by orographic effects; moist air masses are forced to higher altitudes where condensation occurs causing rainfall or snow deposition. The dense networks of valleys collect precipitation over extensive areas and channel it downstream through the main valleys causing flash floods. It has been demonstrated that in areas with similar geologic, hydrologic, and climatic settings in the Eastern Desert of Egypt, precipitation over the basement complex highlands is channeled downstream as a combination of surface runoff in valley networks and as groundwater flow in the alluvial sediments underlying these valleys, in fractured basement, and in down-dropped sedimentary units within the basement complex (Sultan et al., 2007; 2008; 2011; Amer et al., 2013).

I envision a similar conceptual model for Wadi Feiran watershed in southern Sinai (Fig. 1). The Wadi Feiran watershed (width: 22 km; length: 72 km; area: 1770 km²) includes four water bearing formations: the Quaternary alluvium, Miocene-Post Miocene sandstone, Lower Cretaceous sandstone and fractured basement rocks (Aggour, 2005). The watershed channels precipitation over the highlands (e.g., Saint Catherine and Moses [2285 m a.m.s.l] mountains; Fig. 1) towards the Gulf of Suez coastal plain. Fractured basement and alluvial aquifers prevail throughout the Feiran watershed. Only in, and proximal to the coastal plain do I observe rift-related aquifer systems (e.g., El Qaa aquifer system) within down-dropped blocks (Ahmed et al., 2013). In these areas, the alluvial aquifers are often floored by Miocene-Post Miocene sandstone (i.e., Nukhul Formation) and Lower Cretaceous sandstone (i.e., NSAS) aquifers.
Hydrological settings within the major mountainous ranges of the world are characterized by the occurrence of fractured rock aquifers. In contrast to aquifers dominated by clastic sediments which store and transmit water through pore spaces between individual sediment grains, fractured rock aquifers store and transmit water through crevices, joints and fractures in otherwise nearly impervious rocks. The flow of groundwater in these types of aquifers is controlled by spacing, aperture size, orientation and connectivity of permeable 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, such 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. 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.

Two main types of aquifers are present in the Saint Catherine area: (1) Quaternary alluvium, and (2) fractured basement aquifers within the massive basement which is impermeable except for fractures, faults, joints and shear zones (Shendi and Abouelmagd, 2004). The average annual precipitation over the Catherina volcanics and surrounding granitic rocks in the Saint Catherine area amounts to 50 mm (Abouelmagd, 2003) and
the surface runoff was estimated at 14 million m$^3$/yr (Elewa and Qaddah, 2011). A net groundwater recharge of about 11 million m$^3$ (Elewa and Qaddah, 2011) finds its way through sets of interconnected joints to feed the existing wells in the low-lying fault zones (El-Rayes, 2004) and springs (El-Rayes, 1992).
A wide range of remote sensing and geophysical data were applied in this study.

3.1 Remote Sensing Data

3.1.1 Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Images

ASTER is an imaging instrument attached to the Terra Satellite, which was launched in December 1999 as part of National Aeronautics and Space Administration’s (NASA’s) Earth Observing System (EOS). The ASTER images have 14 spectral bands in the visible and near-infrared (VNIR; spatial resolution: 15 m), shortwave-infrared (SWIR; spatial resolution: 30 m), and thermal infrared (TIR; spatial resolution: 90 m) wavelength regions as well as the stereo-pair capabilities. They offer enhanced opportunities for lithologic, land surface temperature, and reflectance mapping as well as Digital Elevation Model (DEM) extraction.

A total of four ASTER scenes were used to delineate the major structure/features (i.e., fractures, fault traces, shear zones, dikes) within the Feiran watershed. The ASTER scenes were corrected, mosaicked and processed in ways that enhanced the compositional (i.e., lithological and mineralogical) differences (Sultan et al., 1987). DEMs with spatial resolution of 30 m was generated from the mosaicked ASTER scenes. Two main products were generated from the DEM: 1) the watershed boundary and the stream...
network were delineated using the Topographic parameterization (TOPAZ) technique (Garbrecht and Campbell, 1997), and 2) the DEM derivative and the shaded relief images were generated. Stream networks and shaded relief images were used for delineation of minor structures.

3.1.2 Spaceborne Imaging Radar (SIR) Images

SIR is part of an imaging radar system that was launched from the space shuttle Endeavour by NASA in two flights (April and October, 1994). SIR incorporates several radar frequencies which could be used for geological, hydrological, and oceanographic applications. Three common bands of SIR include, C-band (central wavelength: 5.8 cm), L-band (central wavelength: 23.5 cm), and X-band (central wavelength: 3 cm). The SIR-C images (spatial resolution: 30 m) were used to delineate the structural elements in areas where the ASTER data is absent.

3.1.3 Google Earth and Orbital View (OrbView-3) Images

The Google Earth images covering the Feiran watershed are from GeoEye-1 high-resolution satellite launched by GeoEye in 2008. GeoEye-1 has a spatial resolution of 0.41 m in the panchromatic band, and 1.65 m for multispectral bands. GeoEye-1 scenes are available for more than 98% of the world.

The OrbView-3 was launched in June 2003 as a five-year mission and was designed to supply high-resolution imagery of the Earth. The satellite carries a camera to acquire 1 m resolution panchromatic and 4 m resolution multispectral images of the
entire planet. All scenes from both GeoEye-1 and OrbView-3 were tonally balanced and mosaicked. Given the very high spatial resolution of these images, they were used for examining smaller, less regional structural features within the Feiran watershed.

3.1.4 Tropical Rainfall Measuring Mission (TRMM) Images

TRMM is a joint mission between the National Space Development Agency (NASDA) of Japan and NASA, launched in 1997 as part of the EOS missions (Huffman et al., 2007). TRMM provides global (50°N–50°S) data on rainfall using microwave and visible–infrared sensors. The primary rainfall instruments of TRMM are the Precipitation Radar (PR), TRMM Microwave Imager (TMI), Visible and InfraRed Scanner (VIRS), Cloud and Earth Radiant Energy Sensor (CERES), and Lightning Imaging Sensor (LIS) (Kummerow et al., 1998). Instantaneous rainfall estimates are obtained every 3 hours with a 0.25° × 0.25° footprint and continuous coverage from 1998 to the present.

TRMM data, version 3B42.007A, was used in this study to examine the amplitude and the spatial and temporal distribution of rain events over the Feiran watershed. The rainfall events along with the radar images (discussed below) were used to provide insights on, and to validate, the assumption that some of the identified structures are water-bearing.
3.1.5 Environmental Satellite (Envisat) Images

The largest civilian European Space Agency (ESA) mission, Envisat was launched in 2002 with 10 instruments aboard. Because of the unexpected loss of contact with the satellite, the Envisat mission ended on April 2012. One of the main Envisat instruments was the Advanced Synthetic Aperture Radar (ASAR). ASAR operated at C-band with central wavelength of 8.5 cm and spatial resolution of 30 m.

Four ASAR scenes (2 in November 2009, January 2010, and February 2010) covering the entire Feiran watershed were collected and processed. The processing steps involved orbital correction, extraction of multi-looking images, filtering, radiometric calibration, backscatter coefficient calculations and co-registration of the acquired images. The backscatter coefficient values are a function of the dielectric constant; the latter measures the electric properties of the surface materials. The dry soils exhibit low (3-8) dielectric constant values while the wet soils have high values (Wang et al., 2004 and 2011).

For the identified rainfall event (17 and 18 January 2010) from TRMM data, we followed the steps advanced by Sultan et al., 1999 to generate color composites that could visually portray an increase in backscatter values following a precipitation event. The color composites were generated from two ASAR images, one before the rain event and another following the rain event. The scene preceding the rain event was assigned the blue and green components, and the one following the event was assigned the red component.
Areas that witnessed an increase in backscatter coefficient following a precipitation event appeared in shades of red on the composite, whereas those areas that did not have an increase in moisture content appeared in shades of cyan. The color composites were used to validate the assumption that some of the identified structures (i.e. shear zones and faults) act as preferred areas for infiltration and groundwater flow in the Feiran watershed.

3.2 Geophysical Data
3.2.1 Very Low Frequency (VLF) Profiles

The VLF electromagnetic method uses the radio carrier waves of the submarine communications stations of the various navies of the world (Klein and Lajoie, 1980, Paterson and Ronka, 1971). The radiated electromagnetic field from a remote VLF transmitter, propagating over a uniform or horizontally layered earth and measured on the earth's surface, consists of a vertical electric field component and a horizontal magnetic field component each perpendicular to the direction of propagation. The VLF receiver measures the distortion of the normally horizontal electromagnetic VLF flux lines by local electrical conductors. For each field stop, the receiver records the frequency of each transmitting station used, the tilt of the magnetic field (from the horizontal, given as a percentage), ellipticity in the vertical and horizontal planes, and signal strength.

The VLF technique has several limitations. The VLF receiver responds strongly to massive sulfides, as well as to graphitic shear zones; however, the Feiran watershed is not known to contain these types of sulfide deposits or graphitic shear zones, so it is
unlikely that interference would present itself in this form. It is also limited to detection within an approximately 90° fan of strikes (±45° from the radial azimuth to the transmitting station). To adjust for this, the VLF measurements were recorded using two transmitting stations. VLF measurements are also subject to sudden pulsations from the solar wind, which result in rapid deviations of the apparent tilt angle that may last for several minutes. In the event that such disturbances were encountered, data collection was paused or repeated to rule out this possible interference source.

Thirty four VLF profiles (Fig. 2b) were acquired during three (September 2011, June 2012, and July 2013) field trips. Throughout the VLF data collection, the Iris Instruments T-VLF Very Low Frequency Radio Receiver was used. The VLF profiles were acquired along transects perpendicular to the strike of the shear zones during daylight hours, when the overhead ionosphere is well developed (Vallée et al., 1992), using England (GBZ; 19.6 kHz) and Germany (NPM; 23.4 kHz) transmitting stations.

VLF results could be examined directly on tilt-angle versus profile distance plots. Conductors, the source of the VLF anomaly, are located where the tilt angle changes sign (zero cross-over). Alternatively, simple filtering can be applied to remove short-wavelength features (e.g., single-station anomalies) and to shift the peaks by 90°. The four-point Fraser filter (Fraser, 1969) was used to shift the curve so that positive peaks are directly over the conductors.
3.2.2 Magnetic Profiles

The magnetic method is an efficient and effective method to survey large areas in relatively short time. The magnetic survey was used to investigate the subsurface geology on the basis of the anomalies in the Earth's magnetic field resulting from the magnetic properties of the underlying rocks. Generally, the magnetic field due to shallow subsurface features is extremely variable and depends on the magnetic properties (e.g., magnetic susceptibility). Common causes of magnetic anomalies include the presence of dikes, faults and shear zones (Telford, 1990).

A Canadian Scintrex MFD-4 fluxgate magnetometer was used to measure the vertical component of total magnetic field (in gammas or nanoTeslas [nT]) along transects within the Feiran watershed (figure 2b). The total magnetic field, location (latitude and longitude), and time of acquisition were recorded for every station. Magnetic data were collected along 12 profiles in September 2011. Given the fact that the Earth’s magnetic field is subjected to time variations (i.e., diurnal variations), the surveys for each day started and ended with base station readings. The base stations reading were then used to correct for the temporal variations in the Earth’s magnetic field (i.e., drift corrections).
CHAPTER 4

METHODOLOGY

We adopted an integrated (remote sensing, field, geophysics, and GIS) six-step methodology that involved the following: (1) compilation of a multitude of relevant data sets in a GIS environment for visualization and analyses; (2) identification of precipitation events from TRMM for which radar imagery is available prior to and after the event; (3) identification of water-bearing areas that had an increase in the backscattering coefficient values extracted from radar (Environmental Satellite’s [Envisat’s] Advanced Synthetic Aperture Radar [ASAR]) images; (4) identification of the nature (e.g., faults, shear zones, dikes, or wadis) of the water-bearing features and mapping their spatial distribution using visible and near-infrared (VNIR) remotely acquired data sets (Landsat 7 and Google Earth DigitalGlobe Imagery); (5) acquisition of field and geophysical data (magnetic and very low frequency [VLF] electromagnetic) to test whether the water-bearing features and their postulated extension in wadis represent preferred pathways for groundwater flow within the study area; (6) investigation of the impact of water-bearing features on groundwater flow in the Feiran watershed and (7) the results and interpretations were then applied across the Sinai Peninsula.
4.1 Construction of a GIS

The Sinai GIS database incorporates co-registered digital mosaics generated from relevant data sets with a unified projection (type: UTM Zone 36, datum: WGS-1984). Regional data sets for Sinai are grouped into the following categories: Base Maps, Geophysics, Topography, Remote Sensing, Hydrology, and Geology. Each category contains a set of digital layers. These digital products include: (1) Geologic map and data sets for geologic units and structures within Wadi Feiran (scale 1: 500,000) (Klitzch et al., 1987); (2) digital elevation models (DEM, spatial resolution: 30m) generated from raw Level 1A Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) scenes; (3) watershed boundary and stream network distribution extracted from the generated DEMs using the TOPAZ (Garbrecht and Martz, 2003) technique; (4) two Landsat 8 thematic mapper (TM) scenes (scene ID: LC81750402013144LGN00, LO81740402013153LGN00; spatial resolution: 30 m); (5) false color mosaic of VNIR TM band images (blue: 7, green: 4, red: 2); (6) false color mosaic of VNIR TM band ratio images (blue: 5/4x3/4, green: 5/1, red: 5/7) that are sensitive to the content of Fe-bearing alumino-silicates, spectrally opaque, and hydroxyl-bearing or carbonate-bearing minerals, respectively (Sultan et al., 1987; 1988); (7) tonally balanced panchromatic GeoEye-1 image (spatial resolution: 0.41 m) and multispectral bands (spatial resolution: 1.65 m) scenes; (8) distribution of faults, shear zones, felsic, and mafic dykes extracted from geologic maps, GeoEye-1, false color TM, and band ratio images; (9) daily precipitation data extracted from 3-hourly TRMM data; (10) backscatter coefficient scenes generated from four ASAR C-band (central wavelength: 8.5 cm; spatial
resolution: 30 m) scenes (ID: ASA_IMS_IPTDPA20091111, acquisition date: Nov. 11, 2009; ID: ASA_IMS_IPTDPA20091127, acquisition date: Nov. 27, 2009; ID: ASA_IMS_IPTDPA20100120, acquisition date: Jan. 20, 2010, and ID: ASA_IMS_IPTDPA20100205, acquisition date: Feb. 05, 2010); (11) two backscatter coefficient mosaics, the first (ASAR I) was generated from the two scenes predating the precipitation event (17 and 18 of January 2010) and the second (ASAR II) from the those following the precipitation event; (12) A false color composite (blue and green: ASAR I, red: ASAR II) ASAR image; (13) forty two, color-coded, Fraser filtered, VLF tilt angle profiles; (14) seven color coded, magnetic profiles; (15) published well data (location, name, and depth to water table) for fifty two wells (JICA, 1999; Abouelmagd, 2003); and (16) additional well locations (250 wells) extracted from GeoEye-1 images.

4.2 Identification of Precipitation Events for which Radar Imagery is Available

Satellite Rainfall Data was used to identify appropriate rainfall events. TRMM is a joint mission between Japan and United States launched in 1997. TRMM provides global (50°N–50°S) data on rainfall using microwave and VNIR sensors (Kummerow et al. 1998; Huffman et al. 2007). Instantaneous rainfall estimates are obtained every three hours with a 0.25° × 0.25° footprint and continuous coverage from 1998 to the present. In this step, TRMM data (version 3B42.007A) were used to examine the amplitude and the spatial and temporal distributions of rain events over the Feiran watershed. Examination of the TRMM-derived daily rainfall time series shows twelve rain events ranging in amplitude from 15.3 to 34 mm for the time period January 1999 to December 2012. The
rain event that occurred on January 17 and 18, 2010 was selected for radar-based investigations for two main reasons: it is during these two days that the highest amount of precipitation (34mm) amongst the recorded twelve events was reported and it is the only event for which radar scenes were acquired only days before and after the event over the Feiran watershed.

4.3 Identification of Water-Bearing Features from Temporal Radar Imagery

One of the main payloads on the Envisat mission (launched by the European Space Agency [ESA] on 1 March 2002) is the ASAR sensor. Four ASAR scenes were collected and processed to extract the backscatter coefficient values. Routine processing steps including the orbital correction, multi-looking, co-registration, filtering, geocoding and radiometric calibration were applied to the ASAR scenes. Two of the selected images (acquisition date: 11/11/2009 and 11/27/2009) were acquired before a TRMM-derived precipitation event on 17 and 18 January 2010; the other two scenes were acquired (01/20/2010, and 2/05/2010) after the event. Extracted backscatter values are a function of the dielectric constant, which is largely controlled by the moisture content of the imaged material; the larger the moisture content, the greater the dielectric constant, and vice versa (Wang et al. 2004; 2011).

To examine the changes in moisture content across the Feiran watershed, we first generated two mosaics from the individual backscatter images, one from scenes acquired before the precipitation event (Mosaic I), and another from scenes acquired after the event (Mosaic II). A color composite change detection image was then generated
following procedures described in Sultan et al. (1988) from two co-registered mosaics. The composite image was generated to identify changes in radar backscatter coefficient that is controlled by changes in soil moisture content following the selected precipitation event. Examination of the RGB color composite difference image (Fig. 4a) shows two major shades of colors, red and cyan. Areas that show higher moisture content following the rain event will experience an increase in backscatter coefficient and will thus appear in shades of red while areas that show no change in moisture content will appear in shades of cyan. Not all the areas that show in shades of cyan are areas showing no change in moisture content, some of which show no change in radar backscatter because they are not adequately visible to the radar sensor.

Terrain visibility to the radar satellite sensor depends on the orientation of the satellite Line-Of-Sight (LOS) and radar acquisition geometry with respect to that of the surface. Visibility thereby varies within different portions of the same scene depending on local incidence angles which, in turn, are determined by local terrain slope and aspect (Cigna et al. 2014). We estimated the “R-Index” (Notti et al. 2010; 2012) to synthesize the effects of local topography (slope and aspect parameters) and satellite LOS parameters (incidence angle and azimuth). R-Index values (range: -1 to +1) exceeding 0.2 represent targets with medium to very good exposure to satellite LOS, negative values are indicative of layover and foreshortening and are unresolved, and those in between (0 < R < 0.2) have medium visibility.

The R-Index values were multiplied by 100 (Fig 4b). Less than 10% of our area was found to be unresolved, the remaining areas have medium to excellent radar visibility.
Thus, the overall terrain visibility to radar imagery was deemed satisfactory.

4.4 Identification of The Nature of the Water-Bearing Features from DEMs and VNIR Images

Digital elevation models (DEM) and two types of VNIR images (Landsat 7 TM image and Google Earth images) were used to identify the nature of the moisture-bearing features. Landsat 7 acquires reflected light in 8 spectral bands, four of which are in the VNIR wavelength region, two are in the shortwave infrared (SWIR), one is in thermal infrared (TIR), and one is panchromatic. A pair of Landsat 7 TM images was used to generate false color composites over the entire Feiran watershed. Atmospherically corrected reflectance data were extracted from digital numbers (DNs) following procedures described in Sultan et al. (1987). False color composite mosaic image of VNIR TM band ratio were used to delineate major structural elements (width > 30 m) (i.e., dikes [mafic and felsic], fault traces and shear zones). Other structural elements (width < 30 m) were delineated using high resolution Google Earth images.

4.4.1 Delineating Wadi Networks

Valleys generally appear as bright areas on Landsat TM bands, compared to the darker surrounding mountainous terrains (Fig. 5a). The stream network and watershed boundary for the Feiran watershed (Fig. 5b) were extracted from the DEM using the
Figure 4: Envisat ASAR composite image and radar visibility distribution for the Feiran watershed; (a) Envisat ASAR false color composite difference image for the Feiran watershed showing changes in radar backscatter coefficient following a precipitation event on 17th, 18th of January 2010; the composite was generated from radar images acquired before (Sep. 11 and 27, 2009) and after (Jan. 01 and Feb 05, 2010) the precipitation event. Areas that witnessed an increase in soil moisture following the precipitation appear in shades of red, those experiencing little or no change in soil moisture appear in shades of cyan, and areas that are unresolvable on radar imagery are shown in shades of grey. Enlargement of Boxes A, and B on Fig. 4a are shown in Figs. 6 and 7 respectively. (b) “R-Index” image show the effects of local topography (slope and aspect parameters) and satellite LOS parameters (incidence angle and azimuth) on the resolving power of radar backscatter images.
Topaz technique (Jensen and Domingue 1988; Martz and Garbrecht 2002) and was validated by comparisons with TM individual bands (Fig. 5a). Inspection of Figure 4a shows that many of the areas experiencing an increase in moisture on the radar imagery mosaic correspond to the distribution of: (1) observed wadi network that is represented by bright areas on TM band 5 image (Fig. 5a) and, (2) wadi network derived from DEM (Fig. 5b).

4.4.2 Delineating Faults and Shear Zones

Faults and shear zones were delineated using the criteria in the field and from satellite imagery (TM band ratio color composites and Google Earth images) include: (1) presence of lithologic linear discontinuities that are tens of meters (faults) to hundreds of meters (shear zones) wide, (2) presence of subparallel topographic ridges within the inferred shear zones, seen in individual band TM images that are probably caused by differential weathering of compositionally different, lithologic units in the shear zones, (3) lateral displacement and/or re-orientation of outcrop patterns of distinctive lithologies and structural trends to align with inferred fault or shear zone in case of strike slip displacements, and (4) sense of lateral displacement on strike slip faults that could be inferred from the changes in direction of structural trends and outcrop pattern of distinctive lithologies as they approach the inferred fault or shear zone. Because the examined satellite images are mostly nadir looking, they are ideal for detecting lateral displacement along strike slip faults and shear zones, but are less effective in mapping dip slip displacement.
Inspection of Figure 6a (enlargement of Box “A”; Fig. 4a), VNIR TM band ratio color composite (Fig. 6b), geologic maps (Klitzch et al. 1987), and our field observations show that the areas showing an increase in moisture content on the radar image correspond to the distribution of: (1) previously mapped faults and shear zones (Klitzch et al. 1987), many of which we verified in the field (Fig. 4c), and (2) numerous lithologic and structural trends of various scales.

Field observations and examination of Figures 6a through 6c show that these sigmoidal features display the following characteristics: (1) many are bounded between adjacent and subparallel faults of similar orientation (largely NW or NE faults), (2) their size ranges from tens of meters to kilometers in length and from tens to few hundreds of meters in width, (3) their sigmoidal shape arises from re-orientation of the original lithologic layering or structural trends to align with the direction of the bounding faults or shear zones, (4) they are highly deformed areas probably because they incorporate intersecting multiple generations of fractures, faults, and shears; and (5) they generally have topographic expressions (e.g., ridge or valley), and/or lithologic expressions (compositional layering).
Figure 5: Distribution of wadi networks in the Feiran watershed; (a) Landsat TM band 5 image showing bright wadis compared to the surrounding mountainous terrains (dark terrain). (b) DEM-derived wadi network and watershed boundary.
Figure 6: Satellite imagery and interpretation map for area covered by box A in Fig. 4a; (a) Envisat ASAR false color composite difference image of the Saint Catherine area. (b) TM band ratio color composite (5/4 x 3/4: blue; 5/1: green; 5/7: red) color composite image. (c) Interpretation sketch map showing the distribution of faults and shear zones that was extracted from Figs. 6a, and b and published geologic maps (Klitsch et al., 1987), observed well locations that were extracted from field observations and Google earth images (red cross) and potential productive well locations at the intersections of shear zones (open yellow circle).
We interpret these observations to indicate that these sigmoidal features represent planes of weakness (fracture, fault, shear zone) that were deformed by younger strike slip fault systems causing them to re-orient and to re-align with the trends of the fault and shear systems.

4.4.3 Delineating Mafic and Felsic Dikes

Mafic and felsic dikes were delineated using satellite and field data. The criteria used for the identification of mafic and felsic dikes in the field and from satellite imagery are: (1) sub-parallel, compositionally homogenous, linear features of large areal extent (hundreds of meters) and limited width (meters) that cut across rock units and sediments of variable compositions, (2) mafic dikes rich in Fe-bearing aluminosilicates (pyroxene) and opaque phases (magnetite, ilmenite), and poor in hydroxyl bearing phases (Lacumin et al. 1998; El-Sayed 2003) appear in shades of blue on the band ratio color composite and as dark streaks on the Google Earth images while felsic dikes which are poor in Fe-bearing aluminosilicate, opaque phase, and hydroxyl-bearing phases (Lacumin et al 1998; El-Sayed 2003) appear in shades of green (fresh), and brown (slightly altered) on the ratio images (Sultan et al. 1987) and as bright buff linear features areas on the Google Earth images.

Inspection of Figure 7a (enlargement of Box “B”; Fig.4a), Google Earth image (Fig. 7b); band ratio color composite (Fig. 7c), geologic maps (Klitzch et al. 1987), and our field observations show that some of the linear features showing an increase in moisture content on the radar imagery mosaic (e.g., a-a`, b-b`, c-c`; Fig. 7) correspond to
the distribution of previously mapped mafic dikes, many of which we verified in the field, on Google Earth images (Fig 7b), and on band ratio color composite (linear blue features; Fig. 7c). None of the investigated felsic dikes show an increase in moisture content on the radar imagery mosaic. The mafic, but not the felsic, dikes are fractured and weathered, especially at their contact with the country rock. We suspect that the weathered and fractured margins of mafic dikes and their surrounding country rock could provide preferential zones for infiltration and groundwater flow.

4.5 Testing (Field Geophysics) Whether the Satellite-Based Water-Bearing Features are Preferred Pathways for Groundwater Flow

Field observations and magnetic data were used to define the postulated extension of the satellite-based water-bearing features in the wadis. VLF techniques were then used to examine the presence or absence of conductive subvertical layers in these locations.

4.5.1 Delineating the Postulated Extension of Dikes, Shear Zones, and Faults in Wadis

Magnetic data were collected (date: September 2011; seven profiles; station interval: 1 to 5 m) in Wadi El Shiekh (Fig. 4b) and surroundings. Figures 8a and 8b are magnetic profiles (m03, m04) that were conducted across selected mafic dikes in Wadi El Sheikh showing high magnetic susceptibilities (peaks ranging from 28902 to 29390 nT) compared to their surroundings; probably due to their higher magnetic content.
Figure 7: Satellite imagery and interpretation map for area covered by box B in Fig. 4a. (a) Enlargement of Envisat ASAR false color composite difference image, showing the red shades surrounding the weathered mafic dike margins. (b) High resolution Google Earth image shows mafic dikes in greenish to dark green lines. (c) TM band ratio color composite (5/4: blue; 5/1: green; 5/7: red) color composite image representing mafic dikes in blue shades according to their composition (plagioclase, pyroxene and amphibole). (d) Interpretation sketch map extracted from Figs. 7a, 7b, and 7c and published geologic maps (Klitsch et al., 1987)
Magnetic profiles were also used to delineate the postulated extension of faults and shear zones in the wadis. Figure 8c shows magnetic reversals along a S-N trending profile (m01) as two subparallel strands of a NE trending shear zone were crossed in Wadi El Sheikh. This response is probably due to shear zone-related lateral displacement that juxtaposed rock units of varying magnetic susceptibilities.

Figure 8: Selected magnetic profiles verifying the extension of mafic dikes under the alluvial fill in wadis. (a) W-E trending magnetic profile (mag03) intersecting N-S trending dike (thickness: 7m). (b) SW-NE trending magnetic profile (mag04) intersecting NW-SE trending dike (thickness: 9m). (c) S-N trending magnetic profile (mag01) in Wadi El Sheikh, intersecting strands of an ENE-trending shear zone.
4.5.2 Detecting Conductive Sub-Vertical Layers Along Water-Bearing Features (Shear Zones, Faults, Mafic Dikes) and Their Postulated Extension in Wadis

A NE-SW trending VLF Profile (1305; Fig. 9) was conducted along a transect perpendicular to a NW trending sinistral shear zone that defines the location of a wadi (average width: 200m) that intersects Wadi El Sheikh. The NW trending shear zone (defined by black dashed lines; Figs. 9a, 9b, and 9c) is characterized by subparallel topographic ridges and interleaving wadis. As the shear zone is approached all structural elements (e.g., ridges, valleys) reorient to align with the shear zone (e.g., yellow lines, Fig. 9b). These structural trends show as blue and dark green streaks (ridges) separated by subparallel pale green streaks (valleys) on the band ratio color composite (Fig. 9a), subparallel NW-trending red streaks (wadis) separated by cyan areas (ridges) on Envisat ASAR false color composite difference image (Fig. 9b), and as subparallel ridges (bright ridges) separated by sparsely vegetated valleys (darker valleys) on the Google Earth image (9c).

At the SW part of the profile, a large anomaly (Fraser tilt location “a” >40%; Fig. 9d) was observed and halfway through the profile, an even larger anomaly (Fraser tilt: location “b” 90%; Fig. 9d) was recorded at the intersection of the profile with narrow (width: <10 m) wadis within the shear zone. Additional VLF-profiles (1107, 1102, 1206 and 1313) were measured across additional NW-trending shear zones, all of which showed one or more peaks with Fraser tilt ranging from 15 to 20% indicating that many of these NW-trending shear systems act as conductive sub-vertical layers.
The Saint Catherine area is dissected by another major set of shear zones trending NE to ENE with dextral motion (Fig. 6c). A S-N VLF profile (profile 1103) was conducted along Wadi El Sheikh perpendicular to a major ENE-trending shear zone (defined by black dashed lines; Figs. 10a and 10b). A close up (Fig. 10c) reveals that the dextral displacement along the shear zone is concentrated along strands within the shear zone where intense brittle deformation was observed in the field. A southern strand extends along an ENE tributary of Wadi El Sheikh and a northern strand passes by a productive well (El Halwagy well) in Wadi El Sheikh. Theses strands are characterized and bordered by subparallel topographic ridges (blue streaks, Fig. 10a; cyan streaks; Fig. 10b; dark ridges, Fig. 10c) and valleys (pale green, Fig. 8a; red streaks: Fig. 10b; bright valleys, Fig. 10c).

The Fraser filtered data showed a peak (Fraser tilt location “a” >70%; Fig. 8d) at the intersection of the postulated extension of the southern strand and Wadi El Sheikh and another (Fraser tilt “location b” 20%; Fig. 8d) further north along the intersection of the northern strand with Wadi El Sheikh. Additional VLF-profiles (1303, 1307, 1308, 1309 and 1310) were measured across numerous ENE-trending shears. For all except profile 1308 large tilt angles (range: 17% to 25%) were measured indicating that many of the shear systems act as conductive sub-vertical layers, and by inference contain water.

A west-east trending profile (1301; Figs 11a through 11e) was conducted along the wadi that leads to the Deir (Monastery) Saint Catherine (Fig. 11d); the wadi is defined by a major NW-SE trending sinistral shear zone (blue dashed lines; Figs. 11c, 11d). The sinistral shear set is intersected by a dextral NE-SW trending shear set (green dashed...
lines; Figs. 11c). These NW and NE-trending shear zones appear in shades of red on the radar mosaic (Fig. 11b). As the shear zones are approached, all earlier structural elements and fabrics are reoriented to align with the trend of the shear zone (e.g., grey lines; Fig. 11c, 11d). Along the shear zones subparallel topographic ridges and valleys are observed in the band ratio color composite and/or wide valley as is the case with the NW shear zone (Fig. 11a). Profile (VLF-1301) intersects the NW-SE and the NE-SW trending shear zones, both of which appear in shades of red in the Envisat ASAR false color composite difference image indicating increased soil moisture following the 17 and 18 of January 2010 rain event (Fig. 11b).

The Fraser filtered data (Fig. 11e) showed high tilt angles (location “a” 76%, “b” 27% and “d” 34% at the intersection of the postulated extension of the NW shear zone and NE trending faults marking locations of valleys separating subparallel topographic ridges) (Fig. 11a). Examination of Fig. 11b shows that many of the moisture-bearing areas appear as sigmoidal features subtended by pairs of sinistral NW or dextral NE-trending faults or shear zones. The sigmoidal shape results from the re-alignment of structural trends and fabrics to align with the direction of the subtending faults and shear zones.

A NE-trending profile (1106: Fig. 12a & c) was measured in the El Berkah area across a NW-trending mafic dike (thickness: 13 m); the dike is dissected by NNE-trending shear zones, (Fig. 12a). The word “Berkah” in Arabic means a “pool of water”; the name was assigned by the bedouins to refer to a pool of water where the dike intersects the wadi, also the location of a small farm that collects water channeled by the
mafic dike (Fig. 12b). Figure 12c is an enlargement of the box in Fig.12a which shows the highly weathered and fractured zone that surrounded the mafic dike margins. Tilt angles were high (20%; Fig. 12d) at the weathered country rocks around margins of the mafic dike, compared to the central part of the dike (Fig. 12d).

The dike margins were chilled, weathered and fractured, as were the intruded country rocks, whereas the central parts of the dike were massive and less fractured. Additional VLF-profiles (1101, 1104, 1105, 1106, 1108, 1109, 1110, 1201, 1202, 1203, 1204, 1209 and 1215) were measured across numerous mafic dikes. For all measured profiles measured tilt angles ranged from 20 to 25% indicating that most of the mafic dikes have margins that are and the fractured and weathered zone and act as conductive sub-vertical layers. Those that have unweathered and unfractured margins are uncoductive (impermeable)(VLF-1110, 1203 and 1204).
Figure 9: Use of VLF data (VLF 1305; Fig. 2b) to verify the conductive nature of the sinistral NW-SE trending shear zone. (a) Band ratio color composite image. (b) Envisat ASAR false color composite difference image. (c) Google Earth image showing the location of the SW-NE trending VLF profile with respect to the shear zone. (d) VLF 1305 profile. Also shown are the boundaries (dashed black line; Figs. 9a, 9b, and 9c,) of the NW-SE trending shear zone and lithologic and structural trends (yellow lines; Fig. 9b).
Figure 10: Use of VLF data (VLF profile 1103; Fig. 2b) to verify the conductive nature of the dextral ENE trending shear zone. (a) Band ratio color composite image. (b) Envisat ASAR false color composite difference image. (c) Google Earth image showing the location of the S-N VLF profile (1103) with respect to the ENE trending strands of intense brittle deformation (black dashed lines) within the shear zone (white dashed lines). (d) VLF profile 1103. Also shown are the boundaries of the ENE-trending shear zone.
Figure 11: Use of VLF data (1301 VLF profile; Fig. 2b) to verify the conductive nature of the sinistral NW-SE shear zone and the sigmoidal features using VLF data. (a) Band ratio color composite image. (b) Envisat ASAR false color composite difference image. (c) Interpretation map based on Figs. 11a and 11b showing NW-SE sinistral shear zones/faults (blue lines) dissected by NE-SW trending faults/shears (green lines), lithologic and structural trends (grey lines), and well locations (red crosses). (c) Google Earth image showing anomalies (red and orange circles) along a W-E VLF profile (1301) at the intersection of a NW-SE shear zone (blue dashed lines) and the postulated extension of highly deformed sigmoidal features (grey dashed lines). (d) 1301 VLF profile.
Figure 12: Use of VLF data (VLF-1106 profile; Fig. 2b) to verify the conductive nature of the weathered and fractured margins of mafic dikes and their surrounding country rock using VLF data. (a) Google Earth image showing a NW-SE trending mafic dike, intruded country rock, and surrounding highly weathered and fractured zone observed in the field. (b) Field photo (facing the SE direction) showing a green area at the intersection of a mafic dike with a wadi (El Berkah area). (c) Enlargement of the area outlined by the blue box in Fig. 12a showing anomalies (red and orange circles) along a SW-NE VLF profile (VLF-1106) at the intersection of the profile with the weathered and fractured dike margins and surrounding country rocks. (d) VLF-1106 profile.
4.6 Investigating the Impact of Conductive Features on Groundwater Flow

An approximate potentiometric surface map (Fig. 13a) was prepared from water levels of 52 wells tapping the fractured basement and the alluvium aquifers in the Feiran watershed. The well data were obtained from Aggour (2007). An elevation profile (86 km long) was generated along the entire length of the Feiran watershed in Wadis El Sheikh and Feiran (Fig. 13a) and compared to groundwater levels in 18 wells flooring the two wadis (Fig. 13b). Examination of Figure 13a reveals a general correspondence between topographic and groundwater gradients in the Feiran watershed, consistent with previously published work that indicates that the groundwater flow in mountainous regions is controlled by topography on the regional scale (Toth 2009; Gaber et al. 2009). However, the figure also reveals a spatial correlation between the distribution of major structural elements and shallow groundwater levels upstream from the major shear zones in the Feiran watershed.
Figure 13: Change in groundwater flow direction related to the structural control in Wadi Feiran. a) Landsat TM image over the Feiran watershed showing the approximate groundwater levels (yellow contours), and the regional groundwater flow direction; also shown are locations of traverse A-A’ along Wadi El Sheikh and Wadi Feiran, sections (stretch 1, 2, and 3) along traverse A-A’ where shallow groundwater levels were reported, well locations along traverse A-A’, and the distribution of shear zones (SZ1, SZ2, SZ3, and SZ4). b) Enlargement of area covered by blue box in Fig. 13a (stretch 2) showing the distribution of dike swarms (dark streaks) that are intensively displaced by dextral faults (outlined by blue lines), most of which are dextral in nature. c) Profile along traverse A-A’ showing ground surface elevation, groundwater elevation, and sections (stretch 1, 2, and 3) along the traverse where shallow groundwater levels were reported.
CHAPTER 5

DISCUSSION AND REGIONAL IMPLICATIONS

Because the basement complex in the Feiran watershed is largely massive, the groundwater flow is expected to occur along the more permeable domains represented by the alluvial aquifers flooring the wadi network and by the fractured basement within shear zones, faults, fractures, and mafic dikes. The structural control of groundwater flow locally has been documented in earlier studies (Issar and Gilad 1982; Kusky et al. 1998).

We interpret the observed spatial correspondence of the satellite-based water-bearing features following precipitation events with the location of wadis, major NW-SE and NE-SW trending shear zones and faults, fractures, and mafic dikes as indicating preferred pathways for surface or near-surface water flow along these topographic or structural features. The presence of VLF anomalies along almost all (85%) of the investigated features indicate that these features, hereafter referred to as “conductive features” are in general preferred pathways for groundwater flow as well.

Because the conductive features have higher porosity and permeability compared to their massive surroundings, infiltration through transmission losses will occur along their length. The depth to which infiltration will occur will depend on the thickness of the permeable zone, that is, the thickness of the alluvial aquifer in wadis and the vertical thickness of the permeable zone in faults, shear zones, or within the weathered and fractured: (1) margins of mafic dikes and, (2) the country rock they intrude. A limited
vertical thickness could explain why a few of the investigated features showed an increase in moisture content on radar imagery yet no VLF anomalies. If I were to generalize our findings, I can interpret the majority of the areas showing an increase in soil moisture following precipitation events (red areas on Fig. 4a) as the preferred pathways for groundwater flow. Thus, the groundwater flow is largely controlled by a complex network of preferred pathways encompassing wadis, shear zones, faults, fractures, and mafic dikes. It is reasonable to assume that the groundwater moves along these preferred pathways in ways that ultimately achieve the overall regional groundwater flow shown in Fig. 13a.

Conductive features that are subparallel to the groundwater flow direction are expected to capture groundwater flow (Gudmundsson 2000; Babikera and Gudmundsson 2004), whereas features that intersect the flow at high angles impound the groundwater upstream and reorient the groundwater flow to align locally with their respective trends (Gudmundsson 2000; Babikera and Gudmundsson 2004). The NW to N-S trending features (Fig. 6d), that are subparallel to the regional groundwater flow direction will capture and facilitate the flow along them, whereas the NE trending features that intersect the groundwater flow at high angle (angle >45°) will obstruct the flow and impound it in the upstream direction. Groundwater levels extracted from 18 wells in Wadi El-Sheikh show evidence for impoundment of groundwater in three major stretches along the traverse (“stretch 1”, “stretch 2” and “stretch 3”) (Fig.13). “Stretch 1” encompasses the area upstream of one or more of three major NE-trending shear zones (SZ1, SZ2, SZ3: Figs. 6b, 13a, and 13b). “Stretch 2” is located within and upstream of an outcrop of G2
Granite that is intensively dissected by NE-trending right-lateral strike slip faults (Fig. 13c) as evidenced by the observed displacements of the dike swarms at their intersections with the faults. Stretch “3” is upstream from a major NE-trending shear zone (SZ4, Figs. 13a and 13b). If the NE-trending shear zones and dike swarms are impeding groundwater flow, one would expect to observe: (1) elevated groundwater levels within and upstream from, the areas dissected by the shear zones and dikes, and (2) a drop in groundwater level downstream from these areas.

Inspection of Fig. 13 shows that this is indeed the case. Stretch “1” within and upstream from shear zones SZ1, SZ2, and SZ3, “Stretch 2” within and upstream from the highly faulted dike swarm area, and “Stretch 3” upstream from SZ4 shear zone display a relatively shallower groundwater depths compared to neighboring areas lacking these features.

The intersections of the NW and NE trending shear zones enhance porosity and create conditions favorable for hosting groundwater in fractured basement rocks. This conceptual model is supported by: (1) the presence of productive wells at the NW and NE trending shear zones in the Feiran watershed (Haroun, Zeitona, El-Watia, and Sahab wells; red crosses, Figs. 1, 6c) and (2) conventional resistivity data (Shendi and Abouelmagd 2004) at these four locations that revealed thick saturated fractured basement aquifer at these intersections (Haroun well: 13.8 m; Zeitona well: 10 m; El-Watia well: 8.7 m; Sahab well: 14.3 m) compared to thin (few meters) fractured basement aquifer upstream and downstream from the intersection locations. Our findings suggest additional potential groundwater accumulations are likely to be found at the intersection
of the NE- and NW-trending shear zones in the Saint Catherine area. These locations for potential productive wells are represented by open yellow circles on Fig. 6c.

Similar findings were observed in Central Sinai in areas north of the Feiran watershed. Examination of the head data from 25 deep wells (Rosenthal et al. 2007) tapping the Lower Cretaceous aquifer NSAS (Fig.1) reveals structural control on groundwater flow. The south to north groundwater flow (Abouelmagd et al., 2014) in the NSAS is intercepted by orthogonal (E-W trending) dextral shear zones, the most prominent of which, is the Themed shear zone (TS) and the Sinai Hinge Belt (SHB) (Moustafa et al. 2013) (Fig. 1). As is the case with the fractured basement aquifer, these shear zones impede the groundwater flow causing a considerable hydraulic head drop (e.g. across the Themed shear zone; from 467 m to 248 m) and a dramatic change in the regional flow direction from a south-north trend towards the Mediterranean Sea to a southwest-northeast trend across the political boundaries into Israel (Fig. 1).
CHAPTER 6

SUMMARY AND CONCLUSION

I conducted an integrated approach using geophysical, remote sensing and field data sets and applied GIS technologies to investigate: (1) the role of structural elements in controlling the groundwater accumulation and flow and to (2) identify the distribution of aquifers in the fractured basement in the Saint Catherine area, southern Sinai, Egypt. The following steps were undertaken to achieve these goals. I identified the spatial and temporal precipitation events over the basement complex from TRMM data and extracted from temporal change in backscattering values in radar following one of the identified precipitation events. The increase in backscattering was attributed to an increase in moisture content and the areas showing the increase in backscattering values were identified as preferred pathways for surface water infiltration. To investigate the nature of these areas and/or features, I correlated their distribution with observations extracted from field observations, remote sensing, and published geologic data and concluded that the moisture-bearing features are mostly fractures, faults, shear zones, mafic dike swarms, and wadi networks.

The majority of the investigated features were determined to be preferred subvertical pathways for groundwater flow as evidenced by the observed high Fraser-filtered VLF tilt values that were measured across the identified features. These features trend in various directions and thus, locally the groundwater flow is controlled by the
conductive features; however, groundwater flow is controlled regionally by topography as evidenced by the observed general correspondence between topographic and groundwater gradients. The general groundwater flow direction in the upstream is from the SE to NW and thus the NW-SE to N-S trending conductive features are more likely to capture the groundwater flow given that they intersect the flow at low angles; the NE-SW to E-W conductive features intersect the flow at high angles and impound the groundwater upstream. Because the NW-SE features capture, whereas the NE-SW impede, the flow, their intersections often represent areas of groundwater accumulation as evidenced by the presence of productive wells at a few intersections.

Similar findings were observed in Central Sinai, where examination of the head data from 25 deep wells tapping the NSAS revealed structural control on groundwater flow. The south to north groundwater flow is impeded by the E-W trending dextral TS and SHB shear zones as evidenced by considerable hydraulic head drop across the shear zones. The faults also cause a dramatic change in the regional flow direction from a south-north trend towards the Mediterranean to a southwest-northeast trend across the political boundaries into Israel.

Deciphering groundwater flow in sedimentary aquifer systems is straightforward once head data becomes available; this is not the case in fractured basement aquifer systems. These systems are heterogeneous in their porosities and permeabilities, making groundwater flow only possible along preferred pathways that are largely controlled by the distribution and connectivity of wadi networks and structures. Our studies indicate that backscattering difference images (e.g., Figs. 4, 6a, 7a, 9b, 10b, 11b) could be used as
a first order map guide for the groundwater flow distribution in basement terrains. These findings should be further validated using geophysical methods similar to those applied in this study and others (e.g., seismic refraction, resistivity sounding and profiling, ground penetrating radar) that could provide a detailed 2D subsurface image. The advocated integrated (remote sensing, geophysics, field, GIS) methodologies are straightforward, practical and cost-effective and could potentially identify the distribution of water resources in many similar arid fractured basement terrains world-wide.
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APPENDIX B

Dikes Distribution In Wadi Feiran Watershed
APPENDIX C

Dikes Distribution In Wadi Feiran Watershed- Composite Ratio Image

APPENDIX D
Dikes Main Trends In Wadi Feiran Watershed

Felsic Dikes

Felsic Dikes
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doi: http://dx.doi.org/10.1017/S0016756800012085


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