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An integrated approach for identification of potential aquifer zones in structurally controlled terrain: Wadi Qena basin, Egypt

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ABSTRACT

Wadi Qena basin represents one of the most promising regions for future development in Egypt. Fresh water supplies are crucial for such plans. We provide an integrated remote sensing (Landsat, ASTER DEM, Geoeye-1), geophysical (aeromagnetic), isotopic ($\delta^{18}O$, $\delta^{2}H$), field (stratigraphic and structural interpretation) and geochemical (major dissolved ions) approach to delineate zones of potential groundwater resources in Wadi Qena basin. Four water-bearing horizons were sampled: fractured crystalline aquifer, Nubian Aquifer System (NAS), Post Nubian Aquifer System (PNAS) and the Quaternary aquifer. Findings include: (1) spatial analysis of remote sensing data in a GIS environment indicates extensive structural deformation by dextral faults trending NE-SW (i.e. Qena-Safaga shear zone [QS]) and sinistral faults trending NW-SE (i.e. Najd shear zone) and sufficient surface water supply from the east through Wadi Fattera sub-basin; (2) analysis of geophysical data indicates that these faults control the water-bearing horizons in the subsurface; (3) isotopic analysis reveals four isotopic groups including two end members, one mixed group and one mixed and evaporated group: group (I) highly depleted fossil Nubian waters (range: $\delta^{18}O$ from −6.39 to −6.74‰ and $\delta^{2}H$ from −48.21 to −52.46‰); group (II) modern waters in fractured basement (range: $\delta^{18}O$ from −1.41 to −1.51‰ and $\delta^{2}H$ from 5.46 to −6.04‰); group (III) a mixed cluster between NAS and modern waters (range: $\delta^{18}O$ from −4.82 to −5.05‰ and $\delta^{2}H$ from −33.28 to −38.54‰); and group (IV) samples which have both mixing between the Nubian and meteoric waters and also have a considerable deviation from the Global Meteoric Water Line (GMWL) (range: $\delta^{18}O$ from −0.58 to −4.69‰ and $\delta^{2}H$ from −19.59 to −38.68‰), (4) samples with a mixed isotopic signature (in group III), which tap the NAS and are located along the main channel of Wadi Fattera (area 3600 km^2) provide evidence for modern recharge along surface exposures of the NAS and enhanced infiltration along deep-seated faults; (5) samples with a mixed isotopic signature (in group IV), which tap the Quaternary and PNAS aquifers and are located along deep-seated faults provide evidence of artesian upward leakage from the deep NAS into the shallower Quaternary and PNAS aquifers. The present study improves our understanding of the role of structural control and modern recharge in exploration for aquifer potential in arid environments.

1. Introduction

The current water shortage in Egypt and the possibilities for additional deficits in River Nile water if the Nile Basin countries proceed with building dams is steering the Egyptian Government efforts to locate additional new water resources. The Nubian Aquifer System (NAS) is one of the largest aquifers in the world, encompassing areas in Egypt, Sudan, Chad and Libya. During previous Quaternary wet climatic periods, the aquifer received enhanced recharge on regional and local scales (Yan and Petit-Maire, 1994; Sturchio et al., 2004; Adelsberger and Smith, 2010). In response to the governmental efforts, several national mega projects have been launched to bridge the gap between the overpopulation problems and shortage of water resources. Examples of these projects are (1) Tushka project (226,800 ha; Sallam et al., 2014), (2) East Oweinate project (42,000 to 79,800 ha; Idris and Nour, 1990; Ebraheem et al., 2003). Wadi Qena basin is among the most promising areas in the Eastern Desert of Egypt. This is because groundwater recharge exceeds the amount in the Western Desert of Egypt; Wadi Qena basin receives an amount of 1.4×10^8 m^3 of modern

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annual precipitation (Milewski et al., 2009). Furthermore, the downstream portion of Wadi Qena basin has (83,757 ha) of almost flat lands that are suitable for reclamation, (Moneim, 2014). Moreover, Wadi Qena is easily accessible through a road network, connecting the densely populated Nile Valley with the touristic Red Sea Province.

As a part of the Eastern Desert of Egypt, the Wadi Qena basin was affected by several structural features (shear zones, faults, folds and fractures), which are attributed to the Pan African orogeny and a series of tectonic reactivations mostly during Cretaceous and Oligocene times (Stern, 1985; El Gaby et al., 1988; Sultan et al., 1988; Akawy, 2002; Akawy and Kamal El-Din, 2006). Despite the degree of structural control in Wadi Qena basin, a comprehensive understanding of the effects of structural control on groundwater flow is still poorly constrained. Generally, structural control of groundwater flow and potentiality for groundwater accumulation varies greatly, from providing high permeable pathways that preferentially force groundwater to pass through or providing low permeability barriers that hamper the groundwater flow. Four factors mainly control the effect of faults and fractures on the groundwater flow including: the aquifer lithology, the hydrological conditions of the aquifer, characteristics of the fault zones and their relation with the hydraulic gradient.

Recently, Abotalib et al. (2016) report on the discovery of intensive groundwater discharge in the Sahara-Arabian desert belt along deep-seated sub-vertical faults during the previous wet climatic periods. They stated that during the wet periods, groundwater table rose significantly and deep groundwater from the NAS accessed the faults and discharged along free faces excavating natural depressions and deep canyons. The regional groundwater table elevation involves areas occupied by three major Aquifers in the Sahara and Arabia including: the NAS, the North Western Sahara Aquifer System (NWSAS) in Libya, Tunisia and Algeria; and the Upper Mega-Aquifer System in Saudi Arabia. If this is the case, one would expect that the artesian upward leakage from deep aquifers to the surface could have been associated with a considerable mixing between deep and shallow aquifers in highly faulted regions which could be a continuous process even under the present day arid conditions. This necessitate a revision to the present understand of groundwater mixing patterns and the role of structural control on groundwater flow in the Saharan-Arabian desert belt.

Remote sensing datasets over the Egyptian deserts enable the mapping of different lithological, structural and geomorphological features at different scales. Because of their multispectral capability and synoptic coverage (Siegal and Gillespie, 1980; Drury, 1987), Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery has been widely used to map lithological and structural elements across the Eastern Desert of Egypt (Sultan et al., 1988, 2008a). Furthermore, integration of multispectral images with radar and elevation data contributed to a comprehensive understanding of the landscape evolution in this area (Abotalib and Mohamed, 2013; Abdelkareem and El-Baz, 2015a, b). In addition applications of remote sensing data to better understanding of the water cycle in the arid environment and groundwater-surface water interactions have been widely implemented (Sultan et al., 2008b, 2011b; Milewski et al., 2009) and satellite-derived rainfall data (e.g. Tropical Rainfall Measuring Mission [TRMM]) could provide a reasonable alternative for the ground-based rainfall measurements (Milewski et al., 2009; Wagner et al., 2009). Airborne geophysical investigations provide regional imaging of subsurface structures. Magnetic susceptibility of different rock types could be used to delineate deep-seated structures along regional scales (Spector and Grant, 1970). Numerous studies have used aeromagnetic data to delineate subsurface structures in Egypt (Bayoumi and Boctor, 1970; Said and Ahmed, 1990; Meshref et al., 1992).

Hydrogen and oxygen isotopes are sensitive to different physical processes (i.e. groundwater mixing, evaporation and atmospheric circulations). Therefore, they are considered as ideal environmental tracers to identify the origin and evolution of groundwater in different climatic settings (Dansgaard, 1964; Clark and Fritz, 1997). Furthermore, chloride (Cl) is a conservative tracer because it is not subjected to adsorption or desorption during transport processes, so it is considered as a good geochemical tracers for solute sources (Fabryka-Martin et al., 1991). Consequently, the integration of geochemical and isotopic tracers could provide clues for differing origins of groundwater components (Sheppard, 1986). Several studies have been conducted using the integration of remote sensing, geophysical, stable isotope, and geochemical data to explore the groundwater aquifers in the Western Desert of Egypt (e.g. Zaher et al., 2009; Abotalib et al., 2016), Sinai (e.g. Becker et al., 2009; Mohamed et al., 2015) and Eastern Desert of Egypt (e.g. Sultan et al., 2007, 2008a, 2011a, b; Amer et al., 2012).

In this paper, we provide a cost effective, interdisciplinary and cutting edge research approach to decipher the ambiguity of the control of structural elements (faults and shear zones) on the groundwater flow in Wadi Qena basin. The approach involves an integration of remote sensing, geophysical (aeromagnetic), stable isotope, chemical and field data to (1) delineate the distribution of structural elements, (2) investigate recharge mechanism to the different aquifers, (3) classify the nature of groundwater within each aquifer based on its isotopic composition, and (4) develop a conceptual model for the role of the structural elements on groundwater flow in the study area. The present study could potentially provide a framework for the developmental plans of Wadi Qena basin and in other similar areas elsewhere.

2. Site description

Wadi Qena basin is located between the crystalline Red Sea Hills in the east and the Limestone Plateau (i.e. El Maaza Plateau) in the west (Fig. 1). The main channel of Wadi Qena basin runs for 246 km from north to south. It is an ephemeral stream that collects occasional rainfall from many watersheds draining the eastern and western highlands and occasionally it receives flash flood events (Moawad et al., 2016). The basin is floored by Cretaceous-Neogene successions of sandstones, shales and limestones.

Wadi Qena basin (surface area: 15,455 km^2) is a unique geomorphic feature in the Egyptian landscape, because it slopes opposite to the regional northward slope of Egypt. This enigmatic morphology was attributed to greater uplift of the northern parts of the Red Sea rift system compared to the southern parts (Garfunkel, 1988). During Miocene time, when a period of intensive erosion prevailed, the landscape of the Eastern Desert developed, giving rise to the formation of numerous valley networks cutting through the Red Sea Hills and El Maaza Plateau (Said, 1993). These valleys join the Wadi Qena master stream and ultimately drain into the River Nile. These drainage networks collect rainwater as a surface runoff in the main streams and as a groundwater recharge to the shallow alluvium aquifer (Sultan et al., 2007). Among 24 sub-basins in Wadi Qena basin, Wadi Fattera is the largest with a surface area of about 3600 km^2 (i.e. about 23.6% of Wadi Qena basin).

Along Wadi Qena basin, several lithological units ranging in age from Precambrian to Quaternary were exposed. The Precambrian crystalline basement complex forms a massive belt oriented parallel to the Red Sea. These rocks consist mainly of metamorphic, acidic and basic igneous rocks which underlie thick sandstones, shales and limestone successions of Phanerozoic age (Said, 1962, 1990; El Ramly, 1972). These successions include (from base to top) the Taref and Quseir Formations of the Nubian Group, Duwi Formation, Dakhla Shale, Tarawan Chalk, Esna Shale, Thebes Group, undifferentiated deposits of Pliocene age and Quaternary alluvium deposits (Klitzsch et al., 1987). In the eastern part of the study area, the Taref Formation, which constitute the bulk of the NAS lithology, crop out at the foot slopes of the Red Sea Hills and/or covered by a few meter thick alluvium deposits (Klitzsch et al., 1987).

Wadi Qena basin was intensively affected by structural discontinuities (i.e. shear zones, faults, folds and fractures). Two prominent shear zones were reported in the study area including: Qena-Safaga shear zone (QS) and the Najd shear system. The QS trends NE-SW with a