Integrated solutions for hydrologic investigations in arid lands

Doris Becker1, Mohamed Sultan1, Adam Milewski2, Richard Becker3, William Sauck1, Farouk Soliman4, Mohamed Rashed4, Mohamed Ahmed14, Eugene Yan6, Ahmad Wagdy7, Kyle Chouinard1, and Benjamin Welton1

1Department of Geosciences, Western Michigan University, Kalamazoo, Michigan 49008, USA
2Department of Geology, University of Georgia, Athens, Georgia 30602, USA
3Department of Environmental Sciences, University of Toledo, Toledo, Ohio 43606, USA
4Department of Geology, Suez Canal University, Ismailia, Egypt
5Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia
6Environmental Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
7Irrigation and Hydraulics Engineering Department, Cairo University, Giza, Egypt

ABSTRACT

Hydrological assessment studies across vast regions of the arid world are often hindered by the inaccessibility of these areas and the paucity of data sets, as well as the high expenses and difficulties entailed in acquiring these data sets, their unpublished nature, and their varying scales, projections, and datum. Using the Eastern Desert (ED) of Egypt (225,000 km2) and the Sinai Peninsula (61,000 km2) as test sites, we demonstrate practical and cost-effective integrated (geochemistry, geophysics, and modeling) solutions that utilize web-based geographic information system (GIS) (http://www.esrs.wmich.edu/webmap) technologies and take advantage of readily available global remote sensing data sets. Adopted methodologies allowed: (1) development of conceptual models for hydrogeologic settings conducive to groundwater entrapment and augmentation, including groundwater in fractured basement aquifers, groundwater impounded by dike swarms crosscutting alluvial aquifers, and groundwater residing in alluvial aquifers associated with ascending deep-seated fossil waters; (2) selection of criteria to identify and validate the preferred distribution of each of these aquifer types and usage of the selected criteria and observations from the GIS data sets to identify, test, and refine potential well locations; and (3) construction and calibration of hydrologic models to estimate average annual recharge over the major watersheds in the Sinai (463 × 109 m3/yr) and ED (171 × 109 m3/yr) and the average modern contributions to Nubian fossil aquifers (Sinai: 13 × 109 m3/yr), and to model the partitioning of precipitation as a function of precipitation amounts.

The successful application of the integrated and cost-effective methodologies developed for the study areas should invite similar applications in arid regions elsewhere.

INTRODUCTION

Increasing populations and limited water supplies increase the demand for fresh water worldwide. This problem is exemplified in arid and semi-arid countries such as those in Saharan Africa (North Africa) and the Middle East, where water resource scarcity contributes to political instability, disputes, conflicts, and terrorism (Amery, 1997). This study aims to develop and demonstrate cost-effective and efficient methodologies to identify, quantify, and integrate additional renewable groundwater resources into the water budget of arid regions. To date, the groundwater potential in four arid regions across three continents (the Eastern Desert [ED] of Egypt, the Sinai Peninsula, the Quetta region in Pakistan, and the Mojave Desert in California) was investigated using the advocated methodologies. We report the adopted methodologies and the findings from the first two regions, the ED (area: 225,000 km2) and Sinai (area: 61,000 km2) (Fig. 1).

For reasons cited below, we suggest that the advocated methodologies are suited for, and could be readily applied to, many of the other less studied arid parts of the world. Data sets needed for hydrological assessments across vast regions of the world are, if they even exist, in many cases expensive, unpublished, difficult to obtain, or created at scales different from other data sets, which complicates their use. The lack of adequate data is compounded by the inaccessibility of vast areas of the world, especially in developing countries; a situation that is hindering scientific research in these areas (Hendrickx et al., 1991; Immerzeel et al., 2008; School et al., 2008). We provide examples in the ED and Sinai of how global remote sensing data sets and applications of web-based geographic information system (GIS) technologies could provide cost-effective methodologies for the assessment of the groundwater potential for vast largely inaccessible areas for which field data is scarce.

We apply an integrated approach in which the GIS provides a vehicle for the integration and analysis of various data to enable the following: (1) development of conceptual models for hydrogeologic settings conducive to groundwater entrapment and augmentation from waters of meteorological origin, (2) selection of criteria to identify preferred well locations that satisfy the settings criteria described above and verifying the validity of the models and selected well locations against existing wells and geophysical observations, and (3) the use of generated GIS data sets for quantitative exploration of groundwater resources via applications of continuous rainfall-runoff models.

In this paper, we integrate a number of stand-alone approaches and methodologies that we developed and/or applied into a comprehensive and cost-effective methodology for the assessment of groundwater potential in arid lands. The advocated integrated methodology is described here in its totality for the first time. Sections describing previously published elements of the adopted methodology are briefly discussed here and reference made to expanded discussions elsewhere, whereas unpublished elements of the methodology are discussed here in detail.
Figure 1. Location map showing the distribution of Neoproterozoic outcrops, the unconformably overlying Phanerozoic rock units including the Paleozoic to Mesozoic age Nubian Sandstone in the ED and the Upper Jurassic to Lower Cretaceous Malha Formation outcrops (primary recharge areas for the Nubian aquifer) in the Sinai. Inset shows the areal extent of the Nubian aquifer in Egypt, Sudan, Libya, and Chad and the distribution of deserts in Egypt, namely the WD, the ED, and the Sinai Peninsula Desert. Also shown are locations for a SW-NE-trending cross section (A−A′) in the ED and a N-S-trending cross section (B−B′) in Sinai (see Fig. 2).
Examples of the former sections include the use of web-based GIS to identify settings conducive to groundwater accumulation (see section “Use of Web-Based GIS to Identify Settings Conducive to Groundwater Accumulation”). Examples of the latter sections include the construction of the web-based GIS (see section “Web-Based GIS Structure”), relevant data sets within the GIS (see section “Web-Based GIS Data Sets”), and web-based applications for the identification of potential well locations (see section “Use of Web-Based GIS to Identify Potential Well Locations (Fault and Dike Related Aquifers)”) and for the display of user-defined model outputs (see section “Use of Web-Based GIS to Construct Hydrologic Models and Display User-Defined Model Outputs”).

**GEOLOGIC AND HYDROGEOLOGIC SETTING**

The two main groups of rock units found in Sinai and the ED are the volcano-sedimentary rock units of the basement complex that crop out along the Red Sea coastline of the ED and in southern Sinai, and the Phanerozoic sedimentary successions that crop out north of the Precambrian complex in Sinai and west of the Precambrian complex in the ED. The basement complex is part of the Neoproterozoic Arabian-Nubian Shield volcano-sedimentary terranes that formed and were later accreted onto an old African Craton to the west some 550–900 Ma; these rock associations crop out along the Red Sea coastlines in the ED and southern Sinai in Egypt, western Saudi Arabia, and eastern Sudan (David, 1984; Engel et al., 1980; Greenwood et al., 1980) (Fig. 1). The Phanerozoic succession includes Paleozoic to Mesozoic Nubian Sandstone in the ED and Upper Jurassic to Lower Cretaceous Malha Formation outcrops, the primary recharge areas for the Nubian Sandstone in Sinai. The inset in Figure 1 shows the areal extent of the Nubian aquifer in Egypt, Sudan, Libya, and Chad and the distribution of deserts in Egypt, namely the Western Desert (WD), the ED, and Sinai. Figure 2A shows a southwest-northeast (SW-NE)-trending cross section in the ED along line A–A′ plotted in Figure 1, and Figure 2B shows a north-south (N-S)-trending cross section along line B–B′ in Sinai plotted in Figure 1 showing similar lithologic and hydrogeologic settings (modified from Milewski et al., 2009b).

---

**Figure 2.** Schematic showing (A) SW-NE–trending cross section in the ED along line A–A′ plotted in Figure 1. (B) N-S–trending cross section along line B–B′ in Sinai plotted in Figure 1 showing similar lithologic and hydrogeologic settings (modified from Milewski et al., 2009b).
By 550 Ma, the major magmatic (e.g., intraplate rifting, anorogenic magmatism) and tectonic activities (e.g., transcurrent faulting related to the Najd shear system) ceased. The Arabian and Nubian Shields remained contiguous until ca. 25 Ma (Bohannon, 1986), when the Red Sea started opening and the shields drifted apart. The Najd shear system is the largest recognized pre-Mesozoic transcurrent fault system on earth (Stern and Hedge, 1985). Using pre-Red Sea rift reconstructions, Sultan et al. (1988, 1992, 1990) showed that the Najd system of the Arabian Shield extends into the central part of the ED, and that the extensive distribution of ophiolitic mélanges in the Central ED can be attributed to the brittle deformation associated with the Najd system. E-W to northeast-southwest (NE-SW)–trending late orogenic dike swarms and bimodal volcanics were reported from Najd-controlled extensional domains in the north ED and Sinai (Genna et al., 1999; Stern and Hedge, 1985). The landscapes of both the ED and Sinai were formed during the Miocene, a time of uplift and intense erosion associated with the Red Sea opening (Said, 1990). The uplift devastated the thick sedimentary successions (largely Eocene limestone and Cretaceous sandstone), but the extensional faults preserved some of these successions as down-dropped blocks under the Red Sea and Gulf of Suez coastal plains and the Red Sea trough.

Two sources of groundwater are present in the study area: modern meteoric precipitation and fossil water (Sturchio et al., 1996). Rainfall over the study areas in the ED and Sinai is generally less than 35 mm/yr and relative humidity is only 15% in summer, rising to 50% in winter (EMA, 1996; Milewski et al., 2009b). Precipitation primarily falls near the Mediterranean coast and over the Red Sea hills; some areas receive up to 250 mm of precipitation per year. Flash flooding occurs every few years in the region (Gheith and Sultan, 2002; Naim, 1995). Precipitation occurs sporadically over mountainous areas near the coasts and is channeled through extensive watersheds as surface runoff in valleys (wadis) crossing these mountainous areas and as subsurface groundwater flow in alluvial aquifers flooring the wadis. Networks of minor valleys in the Red Sea hills in the ED and Sinai merge into main valleys within these watersheds, which ultimately drain into adjacent water bodies (Sultan et al., 2008). Precipitation over the Red Sea Hills in the ED drains toward the Nile River, the Gulf of Suez, and the Red Sea, and in Sinai it flows toward the Mediterranean, the Gulf of Suez, and the Gulf of Aqaba.

Modern precipitation is retained in alluvial aquifers and in fractured basement terrains. Older fossil groundwater is found in deep aquifers such as the Nubian aquifer that was recharged in the Quaternary during previous wet climatic periods (Sturchio et al., 2004). Geochemical and isotopic analyses of samples from the ED and Sinai show apparent mixing of paleo-waters with modern precipitation (Sultan et al., 2011a; Sultan et al., 2007; Sultan et al., 2011b).

**METHODOLOGY AND FINDINGS**

A fourfold exercise was adopted. (1) The adopted methodology calls for the construction of a web-based GIS, compilation of a multitude of data sets, and organization and management of these data sets with the web-based GIS structure, which also provides a vehicle for accessing, visualizing, and analyzing multiple data types (see section “Construction of a Web-Based GIS”). (2) These data sets are then used to apply several hydrological modeling studies aimed at providing a better understanding of the settings conducive to groundwater accumulation (see section “Use of Web-Based GIS to Identify Settings Conducive to Groundwater Accumulation”). (3) This understanding is used to identify potential well locations through manual and semiautomated procedures, taking advantage of the georeferenced data sets and desktop GIS tools imported into the web-based GIS environment (see section “Use of Web-Based GIS to Identify Potential Well Locations (Fault and Dike Related Aquifers)”). (4) Finally, the generated data sets are used to construct calibrated hydrologic models to estimate partitioning (runoff, evapotranspiration, and recharge) of precipitation over the investigated watersheds and to display model outputs as a function of user-defined precipitation amounts (see section “Use of Web-Based GIS to Construct Hydrologic Models and Display User-Defined Model Outputs”).

**Construction of a Web-Based GIS**

**Web-Based GIS Structure**

The web-based GIS system developed for this study is a hybrid system consisting of Google Maps, Python scripts, and ArcGIS Server, which hosts all the services. This combination allows the leveraging of preexisting ArcGIS services while also providing the ability to incorporate more advanced tools. The overall design of the web-based GIS system can be broken up into three distinct parts: data storage, GIS web server and rendering tiers, and the front-end interface viewed by a user. ArcMap is used to create a map file (.mxd) that can then be published to the service. Binary and spatial data are stored in the ArcSDE (Spatial Database Engine), where the ArcGIS Server retrieves the data to process requests for data rendering and manipulation. Requests made by the user through the user interface are sent through the browser to the ArcGIS Server for image rendering. The interface a user would encounter when visiting the web site consists of HTML and Javascript components used to send requests to the server via Asynchronous Javascript and XML (AJAX), and to display images created by the GIS web server at the correct location on Google Maps for the analysis of the data. The map canvas used in this project is the Google Maps API, which allows the web site user to employ the high-quality GeoEye 2 images provided by Google in conjunction with our sensor data, thus providing a more complete view of the area than was previously possible. Users of our web-based GIS can access standard navigation (pan, move, zoom, etc.) available with the Google Maps interface, as well as custom tools such as geoprocessing tools that can graph certain data sets, create an elevation profile, make a displayed layer semitransparent, and apply fitting functions to temporal (monthly) Tropical Rainfall Measuring Mission (TRMM) or Gravity Recovery and Climate Experiment (GRACE) data in search of seasonal patterns in precipitation or mass variations in areas of interest. Next, we demonstrate the data sets available on our web-based GIS, giving examples of how users could use the available data sets and tools to address hydrological questions and issues of interest.

**Web-Based GIS Data Sets**

The Egypt GIS database incorporates co-registered digital mosaics generated from relevant data sets with a unified projection (UTM Zone 36, WGS-84 Datum). Regional data sets for the ED and Sinai are grouped into the following categories in the Egypt GIS, with each category folder containing several data set layers: Base Maps, Geophysics, Topography, Remote Sensing, Hydrology, and Geology. The Base Map folder contains population distribution and georeferenced outlines of national borders. These data sets can be used to orient a user to the spatial location of other data set layers with respect to recognizable borders and population centers in the web-based GIS setting. The Geology folder contains: (1) a geologic color map of Egypt (scale 1:2,000,000), geologic units and ED faults digitized from this map (EGSMA, 1981); (2) a georeferenced, mosaicked geologic map (scale 1: 500,000) (Klitzsch et al., 1987) and data sets...
The Remote Sensing subfolder for Landsat data sets includes (1) six Landsat Thematic Mapper (TM) band mosaics and four band ratio mosaics of the ED and a portion of southern Sinai (~30 scenes, spatial resolution: 28.5 m) created using the Landsat TM reflectance band ratio mosaics (Sultan et al., 1987); (2) a false-color mosaic of Egypt from Landsat TM bands 2 (blue), 4 (green), and 7 (red) (spatial resolution: 28.5 m) created using processed individual reflectance TM bands (Sultan et al., 1987); (3) six Landsat TM band mosaics of Sinai (10 scenes, spatial resolution: 28.5 m) and two false-color mosaics of Sinai from Landsat TM bands 2 (blue), 4 (green), and 7 (red); and (4) Landsat TM mosaic of 23 scenes with Arabia rotated by 6.7° around a pole at latitude 34.6°N, longitude 18.1°E (Sultan et al., 1993).

The Remote Sensing subfolder for TRMM data sets includes monthly, annual, and multi-year totals of the TRMM (spatial resolution: 0.25° × 0.25°) measuring precipitation at 3 h intervals over Egypt. The subfolder for the GRACE Standard Deviation data set consists of a standard deviation of monthly GRACE data (water thickness half degree grids) acquired across northern and central Africa. Individual monthly GRACE mass solutions for the same region are in the GRACE months folder.

The Remote Sensing folder also contains the ED NDVI data set, a Normalized Difference Vegetation Index (NDVI) derived from the Landsat TM mosaic of the ED, and a five-swath mosaic of ASTER band 3 scenes (15 m resolution) over the ED.

The Hydrology folder contains a collection of nine sheets and mosaics of hydrological maps of Egypt (scale 1:500,000) (RIGW, 1992–1998). The Streams subfolder contains (1) drainage patterns for the ED of Egypt, derived from the SRTM (spatial resolution: 90 m) data; and (2) a drainage pattern over Sinai extracted from the SRTM data. The Watersheds subfolder contains (1) watershed boundaries for the ED extracted from SRTM 90 m data; and (2) watershed boundaries for Sinai extracted from the SRTM 90 m data set. The Soils subfolder contains a digitized map of geologic units in Sinai and the ED and a georeferenced map of the soils of Egypt (Hammad, 1975). The Wells subfolder contains georeferenced point locations of existing rain gauges from ~13 stations in the ED and Sinai that provide monthly and daily rainfall amounts (mm) (EMA, 1996; Milewski et al., 2009b).

Use of Web-Based GIS to Identify Settings Conducive to Groundwater Accumulation

Observations extracted from the data sets listed above were used in this study for multiple purposes, examples of which are listed in Table 1, and are here grouped in two main tasks. First, we identify the settings conducive to groundwater accumulation through spatial correlation of existing well locations with observations extracted from various data sets and products (e.g., geologic maps, Landsat, ASTER, TRMM) within the constructed GIS; we apply, refine, and validate these criteria using field and/or geophysical methods (e.g., VLF and VES) to locate potential well locations. Second, we use the generated products (e.g., digitized geologic units, TRMM, NDVI, stream distribution, and watershed boundaries) as inputs to, and verification for, Soil Water Assessment Tool (SWAT) model applications aimed at quantifying the partitioning of modern precipitation into runoff, evapotranspiration, and recharge. Detailed descriptions for such applications are given below.

We identified the following major types of aquifers in the ED and in Sinai (Gheith and Sultan, 2002; Sultan et al., 2011a; Sultan et al., 2008; Sultan et al., 2007): Type 1—modern groundwater in fractured basement aquifers related to intersecting faults, intersecting faults and shear zones, or highly fractured mélangé, all of which are associated with Najd-related brittle deformation; Type 2—modern groundwater impounded by dike swarms cutting across alluvial aquifers; and Type 3—groundwater residing in alluvial aquifers associated with ascending deep-seated Nubian aquifer fossil waters along fault systems bounding the
Red Sea rift system or the River Nile graben. For the purpose of this study, areas of high groundwater potential are here defined as areas where drilling is more likely to yield groundwater.

Criteria for Type 1 Aquifer Identification: Fractured Basement and Intersecting Faults

Highly fractured and deformed basement terrains offer unique settings for hosting groundwater, specifically those structural elements associated with the major transcurrent fault systems that cover domains of large areal extent as is the case with the Najd System. Three types of settings all related at least in part to the Najd System give rise to fractured basement aquifers in the ED and/or Sinai: intersecting faults, intersecting faults and shear zones, or highly fractured mélangé. Observations extracted from the web-based GIS data sets were used to identify these three settings and to extract additional criteria that could be of use in the selection of optimum potential well locations. These include the size of the watershed draining toward the selected site, amount of precipitation over the identified watershed, and presence of natural barriers to surface flow that could enhance opportunities for infiltration and groundwater recharge.

Intersections of two or more fault systems, in many cases represented by intersecting valleys, were identified from Landsat TM images, ASTER images, DEMs, and published geologic maps. In the ED and Sinai, many existing wells are located at the intersection of two or more fault systems that define intersecting valleys (i.e., wadis). These valleys can be identified from Landsat TM images by the relatively brighter spectral signature of the alluvial deposits on the valley floors. The ED contains numerous NW-trending sinistral faults and shear zones and extensive mélanges, all related to the extension of the Najd transcurrent shear system of the Arabian Shield into the central part of the ED (Sultan et al., 1988; Sultan et al., 1990; Sultan et al., 2008; Sultan et al., 2011b). These NW-trending left lateral faults and shear zones were identified from Landsat TM band ratio images that emphasize spectral lithologic variations and de-emphasize those related to topographic variations (Sultan et al., 1987). On these images, serpentinites appear in shades of red, granites in green, and rocks rich in iron-bearing aluminosilicates in shades of blue.

Najd faults and shear zones were mapped from TM band ratio images using the criteria proposed by Sultan et al. (2011b): (1) the presence of NW-trending lithologic discontinuities that are tens of meters (faults) to hundreds of meters (shear zones) wide; (2) a left lateral sense of displacement along the observed lithologic discontinuities as evidenced from the displacement of distinctive lithologies across discontinuities or by changes in direction of structural trends and outcrop patterns of distinctive lithologies as they approach the inferred fault or brittle shear zone; (3) lithologic contacts that are generally tectonic in nature; and (4) the presence of trails of serpentinite along fault traces because serpentinite accommodates movement efficiently at low temperature (Raleigh and Paterson, 1965).

The conceptual model of finding groundwater in areas of high brittle deformation, specifically at the three settings described above, is supported by one or more of the following: (1) the presence of productive wells at targeted locations; (2) geophysical data indicative of the presence of saturated subvertical conductive discontinuities using VLF methods (Palacky et al., 1981; Sultan et al., 2008), as is the case with water-bearing subvertical shears and fault
systems or saturated subhorizontal conductive layers using VES; (3) field observations indicative of high brittle deformation and water saturation; and (4) isotopic compositions of groundwater indicative of meteoric origin. Figure 3 compares the isotopic composition of groundwater from Sinai, the ED, and the WD to that of modern meteoric precipitation.

Using the criteria listed above and Landsat band ratio images that facilitate the mapping of lithologies and structures, a prominent NW-trending serpentinite-decorated Najd shear zone was identified in the Wadi Atalla (Fig. 4; box a in Fig. 1). The intersection of the N-S-trending fracture/fault system that defines Wadi Atalla with the NW-trending Najd shear system was identified as an area of high groundwater potential. The conceptual model was verified and refined using geophysical methods.

The VLF method was adapted to detect steeply dipping shear or breccia zones containing groundwater (Palacky et al., 1981), such as are found in the ED. Four intersecting VLF traverses (lengths: 200–300 and 1200 m) along Wadi Atalla were used to identify six anomalous zones with tilts ranging from 20° to 30° along the traverse (“a” through “f,” Fig. 4A). These high tilt values are indicative of the presence of numerous subvertical conductive sheet layers (Palacky et al., 1981; Sultan et al., 2008), each of which could be the site of a potential location for a productive well. Field observations in the area indicate high brittle deformation in these zones (Sultan et al., 2008). The other geophysical method chosen to investigate possible subhorizontal groundwater accumulations at the base of wadi alluvium, such as where wadis intersect shear zones or faults, was a conventional electrical resistivity system used primarily as VES with expanding electrode spacing (Schlumberger array) at one or more points at a site. VES investigation of this area (Fig. 4B) showed that below a high-resistivity (3279 Ω m) dry, thin surface layer there is a 5 m layer of moderately low (98 Ω m) resistivity, probably fine-grained alluvium containing residual moisture and salts left by evaporation, followed by a thin, high-resistivity (4428 Ω m) layer, probably coarse cobbles; at 6.6 m depth begins a very conductive (20 Ω m) layer of saturated alluvium. The optimum locations for drilling would be those places that have the largest anomalies in a VLF response, preferably identified in more than one VLF traverse, and they should ideally be located where the peak VLF tilt anomalies are observed, indicating the presence of subvertical conductive sheets such as water-bearing high-angle faults and shear zones.

Mélanges were readily identified using the same TM band ratio images; their outcrop

![Figure 3. δD versus δ18O for modern precipitation (IAEA and WISER, 2008), groundwater samples from Sinai including Nubian Sandstone paleowaters (Gat and Issar, 1974; Sultan et al., 2011a), Gulf of Suez thermal waters (Sturchio et al., 1996), the ED (Sultan et al., 2007), and the WD paleowaters (Sturchio et al., 2004). Also shown is the global meteoric water line: δD = δ18O + 10 (Craig, 1961).](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/8/6/1588/3346807/1588.pdf)
patterns exhibit considerable fine-scale heterogeneity on the outcrop scale of meters to hundreds of meters. In the field, lithologic contacts within the mélange area were found to be dominated by tectonic contacts. Two productive wells (Umm Khariga and Bir Ghadir wells; triangles in Fig. 5A, box b in Fig. 1) were reported in wadis crosscutting areas characterized by fine-scale heterogeneous lithologic units that constitute the ophiolitic mélange in the Wadi Ghadir area and surroundings, the area where the largest concentration of mélange was mapped in the ED (Fig. 5A) (Sultan et al., 2008; Sultan et al., 2011b).

In the Sheikh El Shazly area, productive wells (triangle in Fig. 5B, box c in Fig. 1) and proposed wells (circles) are located at the intersection of NW-, NE-, and ENE–trending subvertical fault systems that define valleys (Fig. 5B) plotted on a false-color TM band ratio image (Sultan et al., 1987; Sultan et al., 2008). Field observations acquired from one of the open wells indicated that the host rock is highly brecciated due to these intersecting subvertical fracture systems, and the saturated zone is at a shallow depth in highly fractured metavolcanics that underlie alluvial deposits flooring the valley.

Figure 4. Geophysical data collected along Wadi Atalla that crosscuts a NW-trending serpentinite-decorated sinistral shear zone. (A) TM band ratio color composite (Sultan et al., 1987) acquired over Wadi Atalla area (area covered by box a in Fig. 1) showing Fraser Filtered (FF) VLF tilt profiles (13–2, 3, 4, 5) for a targeted aquifer (fault intersecting shear zone) and the corresponding data plot that indicates the presence of subvertical conductive layers (marked “a” through “f”). Also shown are the location of our VES measurement (blue box), and an enlargement (background: high spatial resolution satellite imagery) of the area outlined by the box. (B) VES showing the presence of a conductive layer of saturated alluvium at 6.6 m depth.
Figure 5. TM band ratio images (Sultan et al., 1987) showing examples of productive and potential well locations in settings conducive to groundwater accumulation; also shown are stream networks in these areas. (A) Fractured basement aquifer in an ophiolitic mélangé in Wadi Ghadir (area covered by box b in Fig. 1) characterized by fine-scale heterogeneous lithologic units and tectonic contacts (modified from Sultan et al., 2008). (B) Fractured basement aquifer in the intersections of fault systems in the Sheikh El Shazly area (area covered by box c in Fig. 1) (modified from Sultan et al., 2008). (C) Aquifer characterized by groundwater impounded by dike swarms (delineated by arrows) intersecting Wadi Abu Zawal (southern) and Wadi Umm Taghir (northern) (area covered by box d in Fig. 1) (modified from Sultan et al., 2008).
The isotopic composition of samples from Sheikh El Shazly ($\delta^D: -14.24; \delta^{18}O: -2.72\%e$) (Sultan et al., 2007) are similar to those of modern precipitation (Fig. 3).

Criteria for Type 2 Aquifer Identification: Dike Related Aquifer Types

Dikes are very common both in Sinai and in the northern part of the ED, where they are often clustered in NE-trending swarms. These dikes vary from tens to hundreds of kilometers in length; they often form in clusters that are kilometers to tens of kilometers apart, some of which have considerable thickness (hundreds of meters thick) and can be traced for long distances (tens of km). Two major trends were reported for the dike swarms in Sinai and the ED. The first dike swarm trend is made up of NW-trending doleritic dikes of Early Neogene (18–22 Ma) age paralleling the Gulf of Suez and Red Sea coastline and intruding Mesozoic sediments in the study area; these dikes are associated with the extensive Red Sea rifting volcanism (Eyal et al., 1981). The second trend is E-W– to NE-SW–trending dike swarms within Najd-controlled extensional domains (Genna et al., 1999; Sultan et al., 2008; Sultan et al., 2007). Depending on their orientation to the hydraulic gradient, dikes can act as barriers to groundwater flow (Babiker and Gudmundsson, 2004). Dikes were readily identified from false-color Landsat and ASTER band and band ratio images. On these images, dikes often appear as swarms of linear features of uniform width. The distribution of these down-dropped blocks could be inferred from observations extracted from data sets contained in our web-based GIS, including: (1) the presence of thick Red Sea-rifting-related down-dropped sediment blocks currently underlying the coastal plains of the Gulf of Suez in the ED (Fig. 6A, box e in Fig. 1) and in Sinai (Fig. 6B, box f in Fig. 1) (Sultan et al., 2011a); (2) the presence of thick Red Sea-rifting-related down-dropped sediment blocks within the coastal plains of the Gulf of Suez (Said, 1990). Paleowaters from the Nubian aquifer (Type 3 aquifer) have been shown to discharge at several locations along the Gulf of Suez (Milewski et al., 2009b; Sturchio et al., 1996; Sultan et al., 2011a).

Productive wells in the ED and Sinai tap Cretaceous–Eocene aquifers hosted in down-dropped blocks now underlying the Red Sea coastal plain, and in outliers of the same rock units in the ED that are found as sedimentary successions packaged within the basement complex and proximal to the coastal plain. Porous sandstone of Upper Jurassic to Lower Cretaceous age is widespread in the northern Gulf of Suez area and is part of a section of Carboniferous through Eocene shales, sandstones, and limestones that unconformably overlie Precambrian basement. This porous sandstone is commonly referred to as the Nubian Sandstone and is overlain by a sequence of Upper Cretaceous through Upper Eocene limestones, dolostones, chalks, and marls that act as a confining unit. Faults control the local distribution and thickness of the alluvial aquifers along the coastal plain of the Gulf of Suez (Said, 1990).

Paleowaters from the Nubian aquifer (Type 3 aquifer) have been shown to discharge at several locations along the Gulf of Suez (Milewski et al., 2009b; Sturchio et al., 1996; Sultan et al., 2011a).

The distribution of these down-dropped blocks could be inferred from observations extracted from data sets contained in our web-based GIS, including: (1) the presence of thick Red Sea-rifting-related down-dropped sedimentary blocks currently underlying the Red Sea coastal plain that could be inferred from regional Bouguer gravity anomaly (scale: 1:500,000) data and from depth-to-basement maps extracted from Total Magnetic Intensity data; (2) the presence of thick Red Sea-rifting-related down-dropped sediment blocks within the coastal plains of the Gulf of Suez (Said, 1990). Paleowaters from the Nubian aquifer (Type 3 aquifer) have been shown to discharge at several locations along the Gulf of Suez (Milewski et al., 2009b; Sturchio et al., 1996; Sultan et al., 2011a).

The conceptual model of finding groundwater upstream from areas where dikes intersect alluvial aquifers flooring the valleys is demonstrated in Figure 5C (box d in Fig. 1), which shows the well called Bir ad Dub at the intersection of a single dike (length: 15 km; width: 30 m) with Wadi Abu Zawal. The figure also shows proposed well locations for similar settings in the area.

Criteria for Type 3 Aquifer Identification: Nubian Aquifer Recharge

Productive wells in the ED and Sinai tap Cretaceous–Eocene aquifers hosted in down-dropped blocks now underlying the Red Sea coastal plain, and in outliers of the same rock units in the ED that are found as sedimentary successions packaged within the basement complex and proximal to the coastal plain. Porous sandstone of Upper Jurassic to Lower Cretaceous age is widespread in the northern Gulf of Suez area and is part of a section of Carboniferous through Eocene shales, sandstones, and limestones that unconformably overlie Precambrian basement. This porous sandstone is commonly referred to as the Nubian Sandstone and is overlain by a sequence of Upper Cretaceous through Upper Eocene limestones, dolostones, chalks, and marls that act as a confining unit. Faults control the local distribution and thickness of the alluvial aquifers along the coastal plain of the Gulf of Suez (Said, 1990). Paleowaters from the Nubian aquifer (Type 3 aquifer) have been shown to discharge at several locations along the Gulf of Suez (Milewski et al., 2009b; Sturchio et al., 1996; Sultan et al., 2011a).

The distribution of these down-dropped blocks could be inferred from observations extracted from data sets contained in our web-based GIS, including: (1) the presence of thick Red Sea-rifting-related down-dropped sedimentary blocks currently underlying the Red Sea coastal plain that could be inferred from regional Bouguer gravity anomaly (scale: 1:500,000) data and from depth-to-basement maps extracted from Total Magnetic Intensity data; (2) the presence of thick Red Sea-rifting-related down-dropped sediment blocks within the coastal plains of the Gulf of Suez (Said, 1990). Paleowaters from the Nubian aquifer (Type 3 aquifer) have been shown to discharge at several locations along the Gulf of Suez (Milewski et al., 2009b; Sturchio et al., 1996; Sultan et al., 2011a).
Figure 6. Contoured Bouguer gravity anomaly data superimposed on color-coded digital elevation data (SRTM: 90 m resolution) covering sections of the coastal plain of the Gulf of Suez and the Red Sea Hills of the ED and Sinai. The spatial distribution of the negative anomalies correlates with that of topographically low areas bounded by NW-SE–to-N-S–trending faults forming a complex array of half-grabens; it also correlates in some cases with locations of productive wells. (A) Coastal plain of the Gulf of Suez and the Red Sea Hills of the ED (area covered by box e in Fig. 1) (figure modified from Sultan et al., 2011b). (B) Coastal plain of the Gulf of Suez and the Red Sea Hills of Sinai (area covered by box f in Fig. 1).
Hydrologic investigations in arid lands

Nubian aquifer groundwater that must have ascended to near surface levels by accessing deep-seated subvertical faults in the proximity of the River Nile (Fig. 2).

The SIR-C with its long wavelength (L-band: 23.5 cm) was used to identify subtle topographic variations across faults that are not easily observed on Landsat images or aerial photographs. Using SIR-C data we mapped the distribution of NW-trending depressions in the highlands surrounding Wadi Asyuti (Fig. 7). The distribution of shallow groundwater samples with fossil isotopic compositions along the projected extension of the inferred depressions from SIR-C images and SRTM data led us to invoke the presence of deep-seated NW-trending reactivated Najd faults that are acting as conduits for ascending fossil Nubian Sandstone groundwater.

Use of Web-Based GIS to Identify Potential Well Locations (Fault and Dike Related Aquifers)

As described in the previous sections, the web-based GIS enables users to select and analyze information portrayed in the georeferenced overlay of data sets together with the developed criteria for identifying structural elements conducive to groundwater accumulation and transport (e.g., faults, dikes, and mélanges) and to test and refine inferences from remotely acquired data sets with co-registered field (e.g., VLF, VES) and well data (e.g., productive well locations, isotopic composition of samples) (e.g., Sultan et al., 2008; Sultan et al., 2008; Sultan et al., 2007; Sultan et al., 2011b). After the identification of aquifer types and a qualitative search and identification of aquifer locations, the analysis of the GIS data sets continues with a search for potential well locations that meet the criteria for promising groundwater potential. This qualitative search using the semiautomated adopted procedures takes advantage of the georeferenced data sets and desktop GIS tools imported into the web-based GIS environment. For example, tools were imported for the preliminary selections of potential well locations at the intersection of two or more faults, a fault and a shear zone, a dike and valley, or within highly deformed mélangé areas.

These initial selections can be further evaluated, refined, and ranked using additional imported tools. The selection of these additional tools was guided by the conceptual models that we developed for the investigated aquifer types. For Type 1 and Type 2 aquifers, the greater the amount of precipitation over the subbasin, the larger the subbasin area, and the smaller subbasin average slope, the larger the amount of recharge across the subbasin and the greater the potential groundwater flow toward the selected point. The presence of existing wells and/or natural vegetation in the selected location provides additional support for the initial selection being a successful potential well location. Examples of the tools developed for the selection and analysis of georeferenced data sets for locating potential new well sites include tools that conduct the following functions: (1) outline the subbasin draining to the selected location based on the DEM topography to better visualize the extent and features of the area that the GIS user is evaluating; (2) calculate the subbasin area, slope, and average annual precipitation over the subbasin draining to the selected location, which allows the user to evaluate whether the location meets project criteria; and (3) highlight existing wells and natural vegetation within a predefined distance from the selected location. Geochemical and other information known about the existing wells is viewable with the standard web-based GIS identify tool.
Use of Web-Based GIS to Construct Hydrologic Models and Display User-Defined Model Outputs

A common practice among hydrologists is investigating the partitioning of precipitation over watersheds into overland flow, channel flow, transmission losses, evaporation on bare soils and evapotranspiration, and potential shallow aquifer recharge (Arnold and Fohrer, 2005; Arnold et al., 1998). We took advantage of the extensive database that was generated to construct and calibrate a continuous rainfall-runoff model to simulate the partitioning of precipitation over the time period 1998–2007, and user-defined model simulations were made available on the web. Simulations were conducted using the SWAT (Arnold and Fohrer, 2005; Arnold et al., 1998), a catchment-based, continuous, semidistributed hydrologic model. SWAT was chosen because the continuous model allows rainfall-runoff and groundwater recharge estimates to be made over extended periods of time, and the input data sets requirements are compatible with GIS data formats, which allow the importation of existing GIS databases for the ED and the Sinai into the model.

The SWAT model was constructed and calibrated using procedures that heavily rely on remotely acquired data sets and applied to the major watersheds in the ED and Sinai (Milewski et al., 2009b). A similar approach was also adopted to quantify the modern recharge to the Nubian aquifer in Sinai that is considered as being largely consisting of fossil water. Figure 8 shows the distribution of outcrops of the Nubian Sandstone in Sinai and the watersheds that incorporate these recharge areas. SWAT simulation results including the average annual partitioning for each of these watersheds or for the Nubian aquifer are available for users on the web-based GIS upon clicking on the polygons defining the watershed of interest or the recharge areas of the Nubian Sandstone. Calibration parameters and their values are given in Table 2 and simulation results are summarized in Table 3.

Results from the SWAT model indicate that the shallow alluvial aquifers in major watersheds in Sinai and the ED (Fig. 9) are receiving an average annual recharge of $463 \times 10^6$ and $171 \times 10^6$ m³/yr, respectively (Milewski et al., 2009b), whereas the largely fossil deep Nubian aquifer in Sinai is receiving a smaller, but not insignificant, modern recharge amounting to $13 \times 10^6$ m³/yr (Sultan et al., 2011a). Transmission losses were assumed to be the only function for recharge of the shallow alluvial aquifers; this is supported by other investigations in arid and semiarid regions with negligible evaporation from stream channels during flash floods (e.g., Abdulrazzak and Sorman, 1994; Ben-Zvi and Shentsis, 2001; Schwartz, 2001; Sorey and Matlock, 1969; Williams and Sharply, 1989).

Figure 8. Distribution of watersheds (red outline) in southern Sinai that encompass Nubian Sandstone outcrops (yellow outline) for which hydrologic models were constructed to simulate average annual modern contributions to the Nubian aquifer. Background: Landsat TM bands 2, 4, and 7 false-color composite image.
and minimal recharge through initial losses from studies in the arid southwest of the United States (e.g., Flint et al., 2000), the Nevada Basin (Dettinger, 1989), and western Saudi Arabia (Bazuhair and Wood, 1996). The recharge to the Nubian aquifer for the decade 1998–2007 in all 20 investigated watersheds combined is found to be 130 × 10^6 m^3. The total area of the investigated watersheds (14,214 km^2) and volume of precipitation (sum of average annual basin values: 1738 mm) suggest that Sinai holds some promise for groundwater exploration. Details of the SWAT modeling have been published (Becker et al., 2009; Milewski et al., 2009a, 2009b; Sultán et al., 2011a).

The calibrated SWAT modeling was also used to examine the variations in the partitioning of precipitation as a function of the precipitation amounts and watershed characteristics. For each of the major watersheds and the Nubian Sandstone outcrops, we ran the calibrated model over the investigation period (1998–2007) using the obtained average annual precipitation and additional values of 10, 50, 100, and 150 mm. The model outputs were then used to extract relationships describing variations in runoff, recharge, and evaporation in relation to average annual precipitation amounts. Using these relationships and user-defined interactive tools, the web-based users could obtain the partitioning of precipitation over any of the investigated watersheds or over the Nubian Sandstone under varying precipitation scenarios of their choice. Figure 10 demonstrates the obtained results for Wadis Watir and Dahab. The observed differences between the watersheds regarding the partitioning of precipitation and their response to increasing precipitation are largely related to the variations in their lithologic characteristics. Watir is dominated (~80%) by Nubian Sandstone and other sedimentary rock unit outcrops, whereas Dahab is largely (~90%) formed of basement outcrops. This explains why more of the precipitation is partitioned as runoff (40%–80% of precipitation) in the case of Dahab and as initial losses (90%–70% of precipitation) in Watir. It also explains why increased precipitation will enhance the partitioning of precipitation as runoff in Dahab and as recharge in Watir.

**SUMMARY**

As described earlier, the paucity of adequate data sets needed for hydrological assessments across vast regions of the world, especially in developing countries, compounded by the inaccessibility of many of these areas, is hindering scientific research. Fortunately, this situation is changing with the development of global remote sensing data sets, which supplement existing data in some areas and in others are the only available data sources. These large data sets acquire measurements with the same observational parameters across large sectors of the land and are not constrained by inconsistencies arising from varying data collection technologies and procedures adopted by various groups.

---

**TABLE 2. CALIBRATED INPUTS USED IN SOIL WATER ASSESSMENT TOOL**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Calibrated value</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN (Alluvial)</td>
<td>63</td>
<td>SCS curve number</td>
</tr>
<tr>
<td>CN (Non-Nubian Sandstone)</td>
<td>74</td>
<td>SCS curve number</td>
</tr>
<tr>
<td>CN (Nubian Sandstone)</td>
<td>70</td>
<td>SCS curve number</td>
</tr>
<tr>
<td>CN (Limestone)</td>
<td>92</td>
<td>SCS curve number</td>
</tr>
<tr>
<td>CN (Precambrian)</td>
<td>94</td>
<td>SCS curve number</td>
</tr>
<tr>
<td>GW_DELAY</td>
<td>0</td>
<td>Groundwater delay time (days)</td>
</tr>
<tr>
<td>ALPHA_BF</td>
<td>1</td>
<td>Base flow alpha factor (days)</td>
</tr>
<tr>
<td>GWQMN</td>
<td>2000</td>
<td>Threshold depth of water in the shallow aquifer required for return flow to occur (mm H2O)</td>
</tr>
<tr>
<td>CH_N2</td>
<td>0.035–0.050*</td>
<td>Manning’s ‘n’ value for the main channel</td>
</tr>
<tr>
<td>CH_K2</td>
<td>225.0</td>
<td>Effective hydraulic conductivity in main channel (mm/h)</td>
</tr>
<tr>
<td>CH_N1</td>
<td>0.035–0.050*</td>
<td>Manning’s ‘n’ value for the tributary channels</td>
</tr>
<tr>
<td>CH_K1</td>
<td>225.0</td>
<td>Effective hydraulic conductivity in tributary channel (mm/h)</td>
</tr>
<tr>
<td>SURLAG</td>
<td>15.0</td>
<td>Surface runoff lag coefficient (days)</td>
</tr>
<tr>
<td>ESCO</td>
<td>1</td>
<td>Soil evaporation compensation factor</td>
</tr>
</tbody>
</table>

*Examination of digital elevation data allowed assignment of areas within a watershed to one of three landforms: mountainous areas, valleys, and foothills; Manning’s ‘n’ values were assigned to the identified landforms following the classifications (mountainous areas: 0.05; valleys: 0.015; foothills: 0.03) by Chow (1959).

The majority of the tributary channels were found in mountainous areas and most of the main channels in the valleys and foothills.

---

**TABLE 3. MODELED AVERAGE ANNUAL (1998–2007) VALUES OF HYDROLOGIC VARIABLES FOR THE INVESTIGATED WATERSHEDS**

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Area of watershed (km^2)</th>
<th>Area of Nubian (km^2)</th>
<th>Precipitation × 10^6 m^3</th>
<th>Initial losses × 10^6 m^3 (%)</th>
<th>Surface runoff × 10^6 m^3 (%)</th>
<th>Watered transmission losses × 10^6 m^3 (%)</th>
<th>Nubian transmission losses × 10^6 m^3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wardan</td>
<td>1161.2</td>
<td>14.9</td>
<td>97.89</td>
<td>86.8</td>
<td>8.9</td>
<td>3.66</td>
<td>3.7</td>
</tr>
<tr>
<td>Gharandal</td>
<td>882.4</td>
<td>77.0</td>
<td>83.65</td>
<td>79.2</td>
<td>0.95</td>
<td>0.97</td>
<td>1.2</td>
</tr>
<tr>
<td>Tayba</td>
<td>356.2</td>
<td>132.3</td>
<td>32.77</td>
<td>27.7</td>
<td>0.84</td>
<td>4.59</td>
<td>14.0</td>
</tr>
<tr>
<td>El-Gart</td>
<td>728.8</td>
<td>55.4</td>
<td>91.62</td>
<td>83.0</td>
<td>0.91</td>
<td>3.80</td>
<td>4.1</td>
</tr>
<tr>
<td>Sidri</td>
<td>1074.6</td>
<td>40.2</td>
<td>111.44</td>
<td>76.4</td>
<td>0.69</td>
<td>6.52</td>
<td>5.9</td>
</tr>
<tr>
<td>Feiran</td>
<td>1806.5</td>
<td>23.7</td>
<td>64.49</td>
<td>29.2</td>
<td>0.45</td>
<td>6.65</td>
<td>10.3</td>
</tr>
<tr>
<td>Durbra</td>
<td>1245.4</td>
<td>7.8</td>
<td>23.8</td>
<td>2.63</td>
<td>0.89</td>
<td>0.04</td>
<td>1.4</td>
</tr>
<tr>
<td>Araba</td>
<td>66.0</td>
<td>10.2</td>
<td>1.80</td>
<td>1.36</td>
<td>0.75</td>
<td>0.07</td>
<td>4.0</td>
</tr>
<tr>
<td>Awag</td>
<td>1943.1</td>
<td>0.81</td>
<td>73.65</td>
<td>46.4</td>
<td>0.63</td>
<td>6.86</td>
<td>9.3</td>
</tr>
<tr>
<td>Near Bir Taba</td>
<td>90.3</td>
<td>31.5</td>
<td>14.21</td>
<td>11.3</td>
<td>0.80</td>
<td>2.35</td>
<td>16.5</td>
</tr>
<tr>
<td>Bir Merakh</td>
<td>50.0</td>
<td>18.5</td>
<td>8.77</td>
<td>4.80</td>
<td>0.55</td>
<td>0.58</td>
<td>6.6</td>
</tr>
<tr>
<td>S. Bir Merakh</td>
<td>37.5</td>
<td>15.1</td>
<td>6.58</td>
<td>1.06</td>
<td>0.16</td>
<td>3.34</td>
<td>50.8</td>
</tr>
<tr>
<td>Near G. Ghazlani</td>
<td>46.1</td>
<td>8.41</td>
<td>8.09</td>
<td>3.80</td>
<td>0.47</td>
<td>1.62</td>
<td>20.0</td>
</tr>
<tr>
<td>N. Ain Quseiyb</td>
<td>31.0</td>
<td>9.92</td>
<td>2.72</td>
<td>1.54</td>
<td>0.56</td>
<td>0.66</td>
<td>24.3</td>
</tr>
<tr>
<td>Ain Quseiyb</td>
<td>54.3</td>
<td>4.45</td>
<td>3.19</td>
<td>2.19</td>
<td>0.69</td>
<td>0.83</td>
<td>26.0</td>
</tr>
<tr>
<td>El-Mahash</td>
<td>47.0</td>
<td>6.87</td>
<td>2.76</td>
<td>1.17</td>
<td>0.43</td>
<td>0.53</td>
<td>19.3</td>
</tr>
<tr>
<td>El-Malha</td>
<td>50.2</td>
<td>8.29</td>
<td>2.98</td>
<td>1.32</td>
<td>0.44</td>
<td>0.50</td>
<td>16.9</td>
</tr>
<tr>
<td>S. El-Malha</td>
<td>50.4</td>
<td>12.3</td>
<td>2.45</td>
<td>1.68</td>
<td>0.69</td>
<td>0.25</td>
<td>10.0</td>
</tr>
<tr>
<td>Watir</td>
<td>3531.4</td>
<td>338.0</td>
<td>208.35</td>
<td>187.0</td>
<td>0.90</td>
<td>2.12</td>
<td>1.0</td>
</tr>
<tr>
<td>Dahab</td>
<td>2082.3</td>
<td>293.7</td>
<td>117.44</td>
<td>64.0</td>
<td>0.54</td>
<td>16.68</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Hydric investigations in arid lands

Geosphere, December 2012

1601
Figure 9. Distribution of the major watersheds (color-filled with delineated streams) in Sinai and the ED for which hydrologic models were constructed and calibrated, and the location of the calibration site (Wadi Paran watershed). Background: Landsat TM bands 2, 4, and 7 false-color composite image (modified from Milewski et al., 2009a).
Hydrologic investigations in arid lands

especially across political boundaries. The use of these data sets is becoming cost-effective, given the large areas covered by these remote observations and the increasing tendencies to reduce their acquisition costs and the expenses (hardware and software) entailed in their processing. Many of these data sets are currently available at no cost to the users. With the development and advancement of GIS technologies, researchers now have vehicles for integrating observations extracted from remote sensing data sets with observations extracted from other relevant data sets (geochemical, geophysical, etc.) for a better understanding of the spatial relationships in the examined data sets on local, regional, and global scales. The advent and applications of web-based GIS platforms (e.g., GIS Server) are now providing cost-effective vehicles for users worldwide to conduct such operations and to distribute data as well.

Using our test sites in the ED of Egypt and Sinai, we constructed a web-based ArcGIS Server with Google Map’s interface and incorporated both standard and customized geoprocessing tools (URL: http://www.esrs.wmich.edu/webmap). These tools, along with Google Map’s API, enable the web site user to utilize high-quality GeoEye 2 images provided by Google in conjunction with our data and custom tools.

Analysis of the generated digital mosaics in a web-based GIS environment allowed for or assisted in the implementation of the following tasks. The first task was the development of conceptual models for hydrogeologic settings conducive to groundwater entrapment and augmentation from waters of meteoric origin; these include: (1) modern groundwater in fractured basement aquifers related to intersecting faults, intersecting faults and shear zones, or highly fractured mélangé, all of which are associated with Najd-related brittle deformation; (2) modern groundwater impounded by dike swarms crosscutting alluvial aquifers flooring the valleys; and (3) groundwater residing in alluvial aquifers associated with ascending deep-seated Nubian aquifer fossil waters along fault systems bounding the Red Sea rift system or the River

Figure 10. Relationships derived from SWAT model simulations for Wadi Dahab and Watir showing the partitioning of precipitation under varying average annual precipitation values. Custom tools on the web-based GIS allow users to apply user-defined precipitation values to extract partitioning model outputs over any of the major watersheds in Sinai and the ED and over the Nubian Sandstone outcrops in Sinai (Figs. 8 and 9).
Becker et al.

Nile graben. The next task was the selection of criteria to identify the preferred distribution of each of these aquifer types, the validation of the models against existing wells and geophysical measurements, and the application of the successful models and relevant criteria to locate potential well locations. The third task was enabling selective interactive GIS modeling operations aimed at identifying, testing, and refining potential well locations. The final task was using the data sets generated for the web-based GIS to construct and calibrate hydrological models to estimate the average annual partitioning of precipitation over all of the major watersheds and the Nile and Sinai and the average modern contributions to the Nile aquifer, as well as variations in the partitioning of precipitation over the major watersheds and the Nubian Sandstone outcrops as a function of the precipitation amounts. Such user-defined modeling applications could be used to examine the impacts of projected climatic variations over areas and time spans of interest. This study contributes to the understanding of the location, nature, and amounts of groundwater in and the ED of Egypt. The successful application of the methodologies developed for the Egyptian deserts invited similar hydrologic investigations in the Quetta region in Pakistan (Sagintayev et al., 2011) and in the Mojave Desert (Dailey et al., 2010) and should serve as a replicable model, especially for similar settings in the less studied arid parts of the world.

ACKNOWLEDGMENTS

Funding was provided by the United Nations Development Programme, the Global Environmental Facility International Water Program; National Science Foundation grant OISE-0514307; the North Atlantic Treaty Organization, Science for Peace Program grant EGSMA, ed.: Wageningen, The Netherlands, Soil Survey Institute. Hammad, M.A., 1975, Geological map of Egypt, Appendix 1 (1:2,000,000), in EGSA, ed.: Cairo, Berlin, General Petroleum Corporation/Conoco, Berlin Institut für Angewandte Geodasie, p. 20.

REFERENCES CITED

Arnold, J.G., and Fohter, N., 2005, Current capabilities and research opportunities in applied watershed model-
Hydrologic investigations in arid lands