Remote Sensing: Generating Knowledge about Groundwater

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FIGURE 1: The Arab Desert Belt as photographed by the Apollon11 astronauts

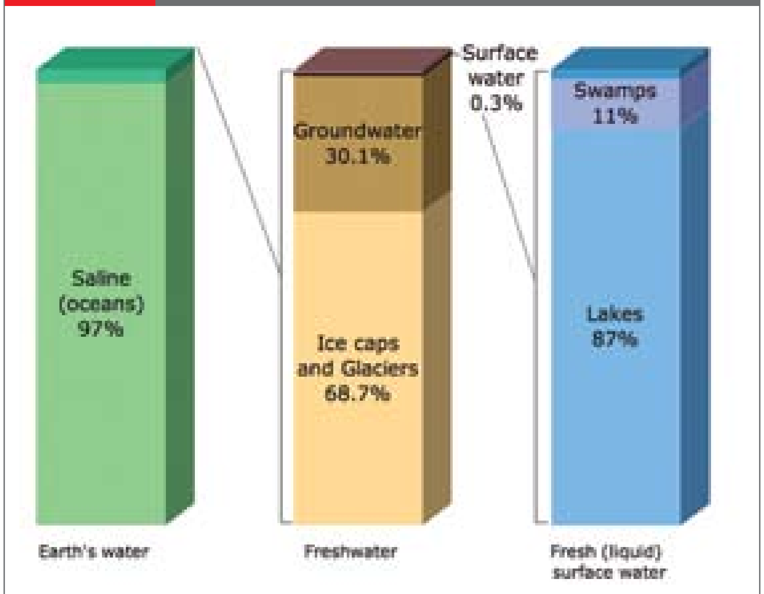
I. INTRODUCTION

Arab countries lie in the driest stretch of land on Earth, which encompasses North Africa and the whole of the Arabian Peninsula (Figure 1). Only three major rivers, the Nile, Tigris and Euphrates, supply narrow strips of land with year-round water. The rest of the region must depend on meager resources, where water for human consumption is provided by desalinating seawater, particularly in the Arabian Gulf countries. However, the remaining countries depend largely on groundwater for human consumption and agricultural activities. Thus, groundwater represents a major source of life in the Arab region.

Sparsely populated regions used to depend on water that percolated through rocks at higher topography to exit in the form of springs – called wahat (oases) in North Africa, oyoun in the Middle East, and aflaj in southern Arabia. These resources were sufficient for sparse populations in the past. However, more recently, large amounts of water were pumped from deep wells where water levels subsided giving the impression that the resources were exhausted.

The reasons for the popular perception that groundwater resources are limited include: (a) too many wells were usually drilled within close distances, in most cases to the same depth; and (b) water was mechanically pumped at rates that were much higher than the mobility rate of water in the pore-spaces of the host rock. These practices resulted from the lack of knowledge of the groundwater environment by both official personnel as well as local farmers. The practices and their results popularized the erroneous notion that groundwater resources are undependable, and that they have been depleted in much of the Arab region. However, the resources are more plentiful if they are mapped thoroughly, used wisely and managed properly.

FIGURE 2 DISTRIBUTION OF WATER ON EARTH



It is instructive here to consider water distribution on planet Earth (Figure 2). Salt water in the oceans and seas constitutes 97% of all water on our "blue planet". Tangible and visible fresh water bodies that leave a marked impression upon us constitute a negligible fraction of the store of sweet water in the remaining 3% of water on Earth. Polar ice masses and mountain glaciers contain nearly 70% of all fresh water. Groundwater represents the remaining 30% -- that is more than 30-times all of the fresh water in all the rivers, fresh water lakes and swamps on the surface of the Earth.

These figures require us to ponder how the invisible water resources are distributed and where they are hidden in order to wisely locate, use and manage them. In the Arab region, groundwater is more prevalent and more extensive than generally believed, particularly in sand covered deserts, which are distant from population centers. It is important to note that such water accumulated during wetter climates in the past. Thus, they are not being replenished today and must be properly managed to ensure sustainability.

II. GROUNDWATER SOURCES

The groundwater story begins as rain water accumulates on the ground surface. The driving force for its movement is gravity where water moves from higher to lower elevations above and within the rock. Water beneath the surface is protected from heating and evaporation by solar radiation and remains locked in the rock fabric for thousands of years. In its journey through the rock, water moves through primary porosity, open spaces between grains of rock, and/or secondary porosity, or permeability that is induced by fractures and faults.

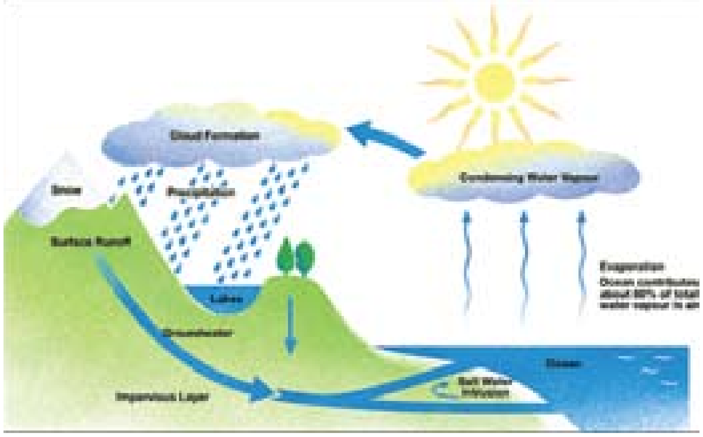
Many people in Arab countries believe that water beneath the surface occurs as lakes or rivers underground. However, water in the ground exists in pore spaces between rock grains or fractures. In the first case, visualize a glass filled with beach sand. The sand fills the glass, but it still has a vast empty volume between the grains. Now fill the glass with water. The latter occupies all the open pore spaces between the sand grains. This explains the nature of the huge aquifers in much of the Arab region.

Rock composed mostly of adjoining sand grains, or sandstone, and others such as limestone have irregular, yet connected pore spaces that allow water passage. In some cases large voids are created by dissolving the host rock to form karsts, caves or dohoul. Water percolates in such rocks to move from a higher to a lower place. Limestone rocks have soluble chemicals and the passing water dissolves the salts. In odd cases, the dissolution of salts within the host rock renders the water saltier than that of the sea.

In addition to pores between grains, surface water passes through fractures in solid rock (El-Baz, 1998a). Although the rock itself may be non-porous, movements of its blocks against each other create porosity. As blocks move along the plain of a fracture, either horizontally or vertically, the rock along that plain of movement is crushed, inducing open and connected pathways that induce secondary or fracture porosity (NRC, 1996). The water can move from higher to lower elevation through these fractures for hundreds of kilometers (Figure 3). It may exist in the form of springs or oases as oyoun or aflaj (Rizk and El-Etr, 1997; Rizk, 1998), and it may pond in the form of a lake, or sabkha, on low desert surfaces at great distances from the water source.

Vast amounts of water seep into the ground through natural (in the rock pores) or induced (fracture caused) porosity (El-Baz and Bisson, 1987). The water originates at high altitudes and continues to descend to lower levels by gravity and stops only when it reaches a saturated or non-porous surface. This is how groundwater basins form, up to hundreds of meters in

FIGURE 3 THE WATER CYCLE



Source: Government of South Africa

thickness, such as the "Nubian Aquifer" of North Africa and the Empty Quarter basin of the Arabian Peninsula (El-Baz, 1998a and b). Here and there, this extensive, seemingly horizontal sandstone aquifer is interrupted by non-porous rock masses, including granitic mountains and volcanic rocks. However, in general it extends beneath the dunes of the Great Sahara or the Arabian Peninsula for vast distances.

III. GROUNDWATER ACCUMULATION

The direction of surface water runoff depends on topography (Figure 3); the greater the degree of tilt the faster the runoff. However, the pattern usually depends on the orientation of faults and fractures in the surface rock. As surface water denudes the rock to establish an easy passageway (Figure 4), a drainage pattern emerges (e.g., Gaber et al., 2010). The pointed tips of the often V-shaped pathways indicate the direction of downward water flow. Such patterns in dry lands indicate the topography at the time of their formation. Thus, analysis of the pattern left on the land surface by running surface water in the past is essential to the prediction of groundwater accumulation.

Similarly, where surface water accumulates in depressed topographic basins, lakes form and may persist for thousands of years. At lake boundaries, terraces form due to the accumulation of rock debris from feeder-rivers and streams. If the lake level changes, for example due to a reduction in the amount of rainfall, a new terrace forms at a lower level. In multi-terrace borders of former lakes, it is possible to date the various levels of the lake by the remains of the biota in the terraces.

This illustrates that for every feature that we can distinguish in the arid lands of today, there is a story of how, when and what mechanism resulted in the surface characteristics. The variety of such features makes it essential to study details of desert surfaces to be able to understand their history. The study of landforms over vast areas of the Arab region requires a bird's eye view, for example, Figure 4. Satellite images provide the best source of information on desert regions, especially for groundwater exploration (El-Baz, 1988, 1998b).

IV. IMAGING SATELLITES

Imaging of the Earth from space has progressively advanced during the past five decades. The first space photographs were those obtained by astronauts from Earth-orbiting spacecraft in the 1960s. Most of these were recorded on color film, which gave us hints as to the nature and composition of the photographed regions. However, more information was provided by the multispectral images.

FIGURE 4 BRANCHING DRAINAGE NETWORK AS DEPICTED IN A SPACE IMAGE

Multispectral images

The more common satellite images were those relayed by digital sensors beginning with NASA's Landsat program in 1972. From the spacecraft altitude of about 900 kilometers above the surface, a sensing instrument looked down at rows of tiny spots, measured the reflected sunlight from each spot, transferred the light intensity values, and beamed the stream of numbers to receiving stations on Earth.

The digital imaging from space allows the use of filters in front of the sensor's lens to separate the reflected light into various wavelengths (Figure 5). It also allows repeat coverage of the same area from the same height by the same instrument for comparisons to detect changes from one time to another. When this is done by overlying the two datasets using computer software, very accurate "change detection" maps are produced (Singh, 1989). This process has been essential to the evaluation of environmental changes, particularly in the increasing use of groundwater in agriculture.

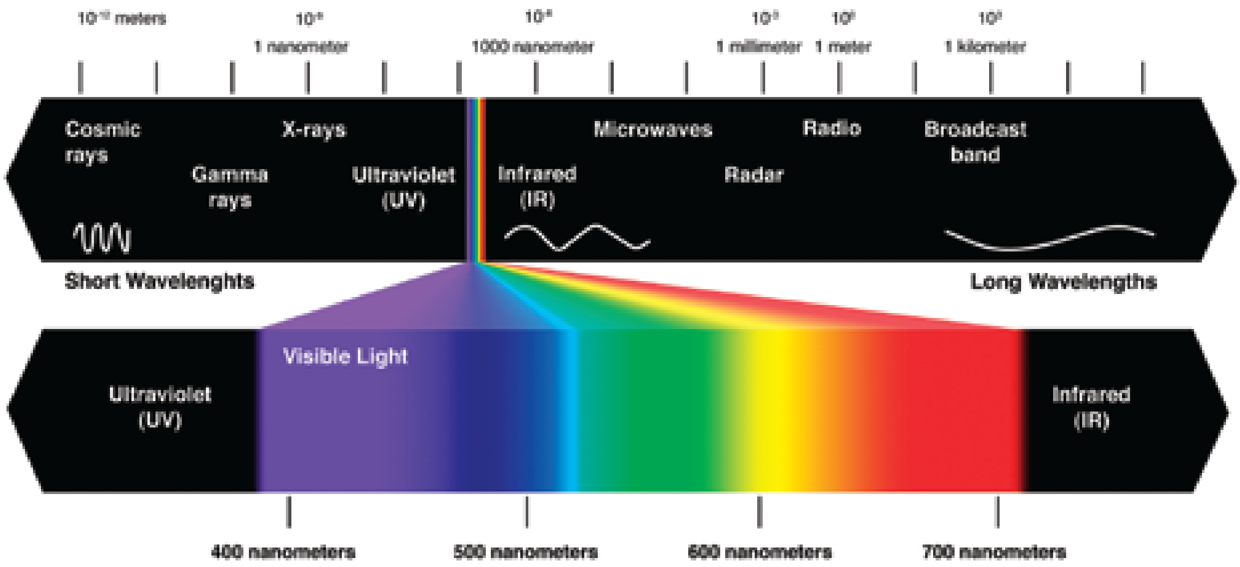
Images acquired by the well known Landsat system, particularly its Enhanced Thematic Mapper (ETM+) sensor, capture data in seven spectral bands. It has a spatial resolution of 30 m in the visible, very near infrared and short wave infrared. It also has a panchromatic band that covers a broad range of the visible with a higher ground resolution of 15 m. In addition, two bands collect data in the thermal infrared region, which are useful in numerous applications; their high spectral resolution makes them suitable for depicting the natural characteristics of the landscape (Lillesand et al., 2004).

The use of multispectral Landsat data is not limited to the physical domain. For example, they can be used to determine the rate of evapotranspiration in irrigated agriculture. Knowledge of evapotranspiration would allow limiting the use of water to specific plant needs.

Thermal data

Cool anomalies that appear on land in thermal data represent water occurrences at or near the surface. This is because the latent heat content

FIGURE 5 THE ELECTROMAGNETIC SPECTRUM

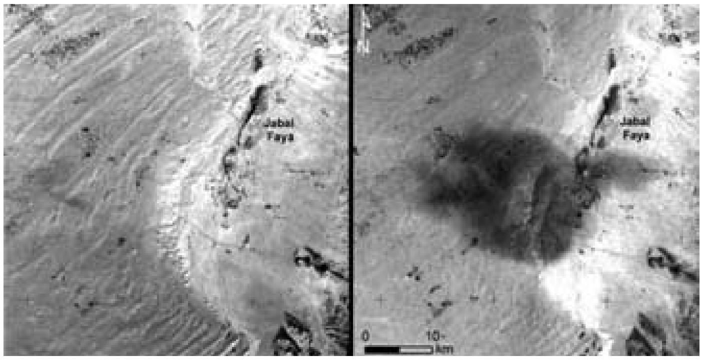


of water (present as moisture in soils) slows the absorbance and emittance of radiation, so that at a given time within the diurnal heating cycle, the warming of the moist soil is retarded (Pratt and Ellyett, 1979). Similarly, cooling during the night is also slowed. Thus, moist soils possess higher thermal inertia, which shows up as cold anomalies in the thermal data collected during daylight hours. Fresh-water seeps into the ocean can also be detected by temperature differences.

Inland thermal anomalies and fresh-water seeps are identified using freely available MODIS data. These data are retrieved for periods after major rainstorm events, the latter being available from the Tropical Rainfall Mapping Mission since 1998. The presence and extent of thermal anomalies are subsequently confirmed using higher spatial resolution Landsat data. Finally, their location and distribution are correlated with the mapped drainage and structural features.

This procedure has been successfully applied to the northern United Arab Emirates (U.A.E.). In this case, a thermal anomaly was identified in the Emirate of Sharjah and linked to rain water passage through a major fault leading to a low region just west of Jabal Faya (Figure 6). Furthermore fresh water seeps into the Gulf of Oman through

FIGURE 6 TWO THERMAL IMAGES OF SHARJAH (U.A.E.) BEFORE AND AFTER RAINFALL ON THE OMAN MOUNTAINS TO THE EAST CAUSING A COOL ANOMALY (DARK AREA) NEAR JABAL FAYA



mountain fractures were also identified by thermal data (Ghoneim et al., 2005).

Imaging radar

The third-generation of satellite images were provided by radar remote sensing (Elachi and Granger, 1982; Elachi et al., 1984). As opposed to the passive sensing of reflected sunlight, a radar sensor emits waves toward the Earth and records the returned beam, or echo. Thus, bedrock surfaces and coarse deposits appear bright, because

FIGURE 7 RADAR WAVES REVEAL ANCIENT RIVER COURSES UNDER DESERT SANDS

of diffuse reflection. However, smooth soils appear dark owing to reflection of the radar waves away from the receiving antenna on the spacecraft. One most significant aspect is the ability of radar to penetrate dry, fine-grained sand to reveal hidden topography (Figure 7). This principle allows unveiling courses of former rivers beneath desert sand. These courses give hints as to the location of groundwater accumulation sites in arid environments. The principle has been put to the test in several localities in the eastern part of the Great Sahara.

The Shuttle Imaging Radar (SIR) was a series of three radar instruments flown on the U.S. Space Shuttle. The third instrument was part of a joint mission to collect the first multispectral and multi-polarization SIR-C/X SAR data contained two co-registered instruments (Jensen, 2000).

Furthermore, Radarsat systems were commissioned by Canada as commercial Earth observation satellites. The first in the series, Radarsat-1 was launched into a near-polar Sun-synchronous orbit 798 km above the Earth. Unlike optical satellites that sense reflected Sun light, radar systems transmit microwave energy towards the surface and record the reflections. Thus, radar can image the Earth, day or night, under any atmospheric condition, such as cloud cover, rain, snow, dust or haze.

High resolution imaging

Ikonos is an example of the commercial high resolution earth observation satellites with a revisit cycle of 11 days. At nadir, its imaging system has a swath width of 11 km and employs linear array technology and collects data in four multispectral bands at a ground resolution of 4 m (Lillesand et al., 2004).

Similarly, QuickBird was launched by Digital Globe, Inc. in a sun-synchronous, relatively low orbit, at an altitude of 450 km, which enables the spacecraft imaging camera to distinguish ground objects 61 cm across. At such high resolutions, details of buildings and other infrastructure are easily visible. Its spectral ranges are equivalent to those of the Ikonos system.

Several other countries launched multispectral imaging satellites, due to their utility in studying the environment of the Earth and its resources. For example France sent a series of SPOT missions, followed by satellites by Russia, India, Japan and China. During the past few years some Arab countries launched imaging satellites. Saudi Arabia began first, followed by Egypt, which now operates a multispectral imaging system with 7.8 meter ground resolution. Algeria is planning one and the U.A.E. is also considering launch and operation of imaging satellites. These systems, although they duplicate area coverage, they bode well for the mapping of resources throughout the Arab region, with particular emphasis on groundwater.

V. METHODOLOGIES

Modern exploration for groundwater resources requires a combination of image processing and geographic information systems (GIS) analysis. It also requires some supporting field and laboratory work for the verification of the satellite derived information. The following section outlines the methods for such research.

Digital data analysis

Image Preprocessing of satellite images to generate maps of drainage systems (surface and near-surface), geologic structures, thermal anomalies, geologic/geomorphologic units and vegetation distribution. Preprocessing operations are carried out before data analysis and include both radiometric and geometric corrections. In radiometric corrections, images collected at different dates and times, and by different sensors, are normalized to each other so they can be directly compared, except for the case of band ratios, which generate relative, and not absolute, values. Geometric corrections counteract sensor irregularities, terrain relief, curvature and rotation of the Earth. These corrections depend on the data type used.

Image Transformation involves multiple bands of data (a single multispectral image, multi-temporal images or multi-sensor images) to generate a single image that highlights particular features or properties of the land surface. Examples of transformations include image subtraction and image ratios. Image subtraction is applied to identify differences or changes between images of the same area but acquired at different dates. Image ratios are applied to obtain or enhance particular information on the status of the land surface. For example, vegetation indices where healthy vegetation reflects strongly in the near infrared and absorbs strongly in the visible red region of the spectrum, compared with soil and water that show near equal reflectance in the red and near infrared.

Image Enhancement procedures are applied at the end to improve image interpretability. They result in changes to the digital values, thus should be the last step to be applied. They can be stretches that work with the image histogram, or as spatial filters that highlight or suppress features based on their spatial frequency.

Mosaicking of individual satellite scenes might result in providing full coverage of an entire country. This process involves three steps: a) re-sampling images to a finer resolution, b) matching the brightness for all images, and c) blending the overlapping regions. In the case of Egypt, a mosaic (Figure 8) was first used to unravel the groundwater story. It clearly showed that sand dune lines are oriented north-south (El-Baz, 1979). This is because the wind in Egypt comes normally from the north. The sand, proven to be made of quartz, had no rock source in the north. In the meantime, exposed rocks to the south were largely composed of sandstone. It was theorized that the sand was not transported from its source by wind but by water from the south. Thus, the search for buried courses of ancient rivers began (El-Baz, 1982, 1988 and 2000).

Image Classification is the use of spectral information in a multispectral image to classify each pixel in order to produce thematic maps that denote different kinds of land cover. There are two primary types of classification: the unsupervised and the supervised. Unsupervised classification is useful for preliminary spectral class discrimination. It is considered to be an exploratory procedure where the classification algorithm determines the spectral categories without supervision by the user. A supervised classification involves a priori knowledge of data to "train" the computer to identify categories in an image based on the information provided (Gaber el al., 2010).

Change Detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh, 1989). There are numerous change detection methods that may relate to groundwater resources in the desert such as determining vegetation differences. Changes between classes in initial and final state images are quantified. Change detection maps are ideal for highlighting the difference in imagery between two times.

Geographic Information Systems

Display and correlation of complex sets of digital information is best done through the use of a structured and relational database. A geographic information system (GIS) offers the basic tools and methodology to create such a database of spatial features with specific properties (attributes) and geo-locations (coordinates).

Data manipulation and analysis in a GIS solve specific research problem. Some data manipulation and analysis tasks are conducted in the raster domain (e.g. surface elevation,

FIGURE 8 MOSAIC OF 65 LANDSAT IMAGES OF EGYPT SHOWING PARALLEL LINES OF SAND DUNES

precipitation, slope) while others in the vector domain (lithology, soil or rock type, land use pattern), depending on parameter characteristics of a particular data set (Gaber et al., 2010).

The GIS output may contain information extracted or derived from a set of map layers by using any combination of analysis operations. The final outputs are dynamic maps in digital form that represent the characteristics of the study region, as will be shown in the case studies listed below.

VI. CASE STUDIES

No contribution is broad enough to cover all possibilities of groundwater occurrences in the Arab region. Below are examples of the eastern part of the Great Sahara of North Africa (Egypt, Libya and Sudan), the Arabian Peninsula (Saudi Arabia and Oman), and the eastern Mediterranean region (Lebanon).

East Uweinat (Southwest Egypt)

The Great Sahara constitutes the largest desert belt on Earth, extending for nearly 6,000 kilometers from east to west. Its eastern part includes some of the driest regions on the planet, where the received solar radiation is capable of evaporating 200-times the amount of rainfall (Henning and Flohn, 1977). This hyper-arid condition necessitates complete dependence on groundwater resources for human consumption and agricultural activities. Increase of populations and the attendant food and fiber needs have exasperated the situation (El-Baz and El-Ashry, 1991).

Although the Sahara is now dry and is subject to the action of strong winds from the north, Archaeological evidence indicate that it hosted much wetter climates in the past (Wendorf et al., 1977; Haynes, 1985; Haynes and Mead, 1987; Haynes et al., 1979 and 1989; Pachur and Hoelzmann, 1991; Pachur and Wunnemann 1996; Pachur and Rottingen, 1997). Surface water during past moist climates led to the formation of lakes in topographic basins. Satellite images represent excellent tools for the study of the desert features (El-Baz, 2000). In addition to the data types described above, use can be made of the Shuttle Radar Topography Mission (SRTM) data that display three-dimensional views of the terrain (El-Baz et al., 2000; Ghoneim and El-Baz, 2007a and b).

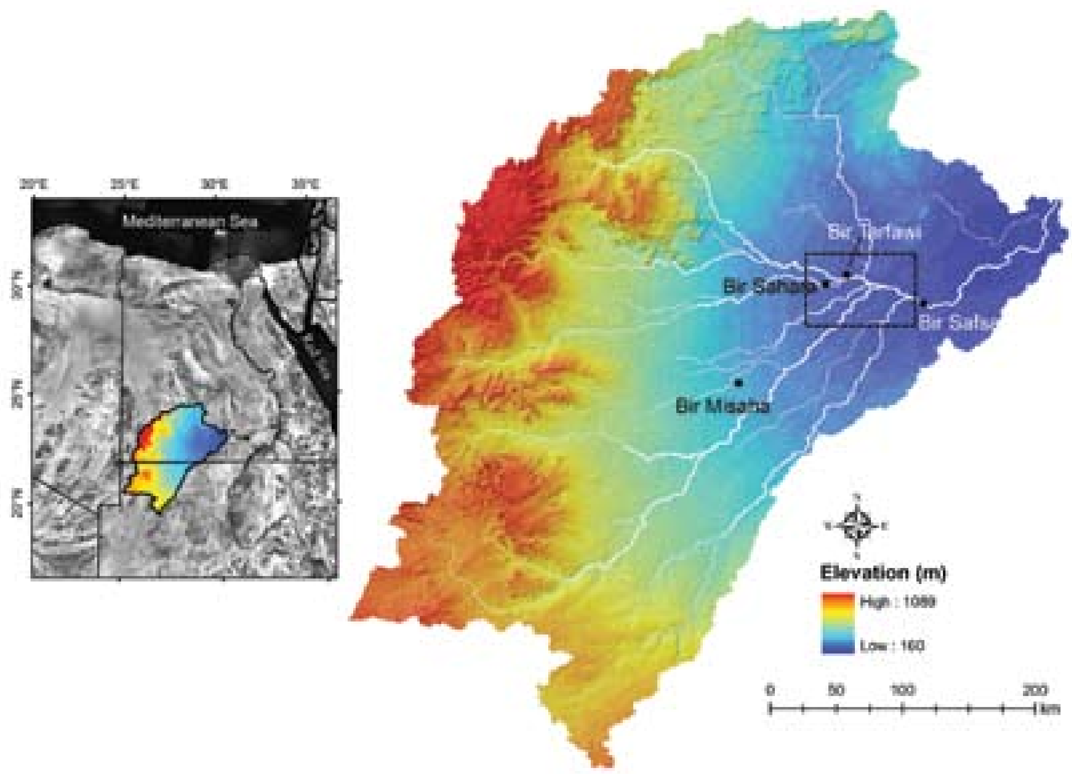
In southwest Egypt, a 300 kilometer flat, sand-covered area straddles the border between Egypt and Sudan. This region is called the Great Salima Sand Sheet, after the Salima Oasis on its eastern border. This oasis is a prominent location along the Darb El-Arbain (the 40-day track) of camel caravans from Darfur in northwestern Sudan to the Nile Valley in Egypt. Many drainage lines uphill of the Great Selima Sand Sheet were revealed by SIR-C images with four major lines leading directly to it from the west (Figure 9). The northernmost drainage system trends due east and measures 150 kilometers in length. The longest and broadest wadi system is aligned in a NE-SW direction. Such broad channels usually develop under sheet flood conditions with plentiful surface water (El-Baz, 2000).

The high resolution, high precision SIR-C data show that several of these broad channels display small braided streams in their floors, indicating several episodes of water flow. Field observations of trenches dug in May 1998 by a joint team of the Egyptian Geological Survey and Mineral Authority and the Desert Institute of Egypt indicate that moisture begins to appear at 25 centimeters depth in the sand cover of shallow channels in the Bir Safsaf region of southern Egypt. This suggests that moisture from occasional rainstorms is carried through, and retained by, the sand fill of the palaeo-channels (El-Baz, 1998b and 2000 and Hoelzmann et al., 2001).

Radar images first revealed the courses of rivers and streams in northwestern Sudan, where the widest channel points toward the region. This setting was interpreted to suggest groundwater accumulation in its eastern, lower-most area. The author made this case repeatedly, starting in 1982, to the Ministry of Agriculture and Land Reclamation of Egypt. Finally, the government of Egypt started in 1995 to drill a few exploratory wells. The latter were monitored for the next five years to assure the presence of large amounts of groundwater. In 2000, plots of 10,000 acres were offered for agricultural development by private sector companies in Egypt.

Today, within this “East Uweinat” region, over 500 wells were drilled to water agricultural fields using circular, spray irrigation. The products include wheat, peanuts and other basic food crops. The wheat, in particular has proven essential for flour production in the mills of Aswan for bread that is distributed in towns of southern Egypt. The proven water resources are capable of supporting agriculture over 150,000 acres for at least 100 years (El-Baz, 1988; Robinson el al., 1999 and 2000). This particular case emphasizes the need to study the desert landscapes in the Arab region to uncover the groundwater potential for the benefit of its people.

FIGURE 9 EAST UWEINAT REGION OF SOUTHWEST EGYPT WHERE RADAR TOPOGRAPHY DATA REVEAL SEVERAL RIVER COURSES LEADING TO A LOW AREA WHERE AGRICULTURAL FARMS ABOUND (BOXED AREA)



In such a hot and dry environment drip irrigation is used for trees and spray irrigation is employed for crops, such as cereals. In the case of spray irrigation, measurements of the evapotranspiration during various seasons would be most useful. It would assure limiting spray irrigation to the essential needs of the crops.

Kufra Region (Southeast Libya)

To the northwest of the East Uweinat region in Egypt, Apollo-Soyuz and Landsat images of southeast Libya show that the Kufra Oasis region is the only inhabited area in this part of the eastern Sahara. The Oasis had been an important stop along the camel caravan route from Chad northward to the Mediterranean Sea. Its circular irrigation farms were developed starting in the 1960s by the Oxidental Oil Company as part of a concession to explore for oil. The farms were visible to Earth-orbiting astronauts due to the contrast between the vegetation and the

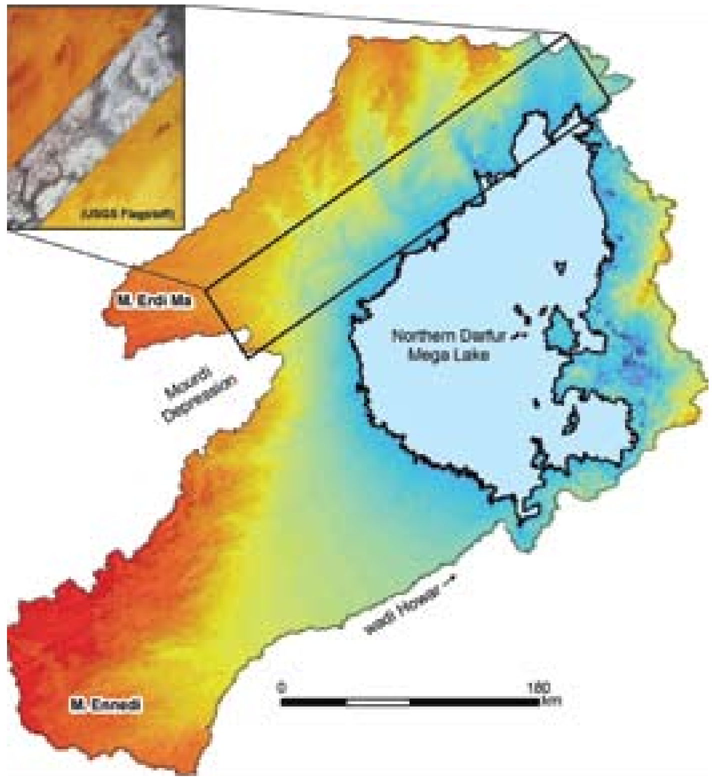
FIGURE 10 SHUTTLE RADAR IMAGE OF TWO ANCIENT RIVERS SOUTH OF KUFRA OASIS, SOUTHEASTERN LIBYA

surrounding sandy plain. This contrast was not only depicted in the visible, but also in the near-infra red, as well as in radar data.

Both SIR-C and Radarsat-1 data revealed courses of two sand-buried palaeo-channels (Figure 10). The longer and narrower western channel, which passed through the Kufra Oasis, originated from the direction of the border with Chad. The wider eastern channel was oriented in a NW-SE direction and originated from highlands west of the Gilf Kebir plateau of southwestern Egypt. Thus, it became clear that the locations of both the Kufra Oasis and the circular irrigation farms were due to the passage of these two former rivers (El-Baz, 2000).

It is notable that the Kufra area is one of five main basins from which water is pumped to supply the Great Man Made River Project of Libya and depends on these two channels. The two rivers that fed the two channels were active during humid phases in the past. Much like the case in Egypt, these channels must have been filled with water during the period from 11,000 to 5,000 years ago. Because some rain clouds occasionally reach the Tebesti Mountain mass, some replenishment of the groundwater occurs in the region through the western channel.

FIGURE 11 THE NORTH DARFUR ANCIENT LAKE AS REVEALED BY SPACE SHUTTLE RADAR AND TOPOGRAPHIC DATA



North Darfur (Northwest Sudan)

The Darfur region (home of the Fur tribe) of northwestern Sudan lies to the south of both the Uweinat region of Egypt and the Kufra area of Libya. It is presently divided into three governorates: northern, western and southern (it is now being considered for division into four governorates). The governorate of North Darfur in particular represents an environment typical of the eastern Sahara of North Africa. The farther north one goes, toward Egypt and Libya, the greater the aridity.

Jabal Marra is a massif that straddles the three governorates. It causes some rainfall, but this is characterized by irregularity in both space and time. Particularly severe droughts over the past two decades initiated years of unrest along the fringe of the Sahel belt of North Africa and caused population migrations that were followed by a vicious war in the Darfur region. Water shortages underlie the initiation of the conflict that had erupted between Darfur's farming communities and nomadic populations. The latter inflicted much damage to numerous farm communities. Thus, there is a need to develop new and innovative techniques to locate additional water resources to satisfy urgent requirements.

In the northern Darfur region, interpretations of space-borne data resulted in the identification of anomalous, arcuate linear features at an elevation of 573 m above present sea level (Ghoneim and El-Baz, 2007b). Detailed geomorphologic analysis of these discontinuous linear features confirmed that they were remnants of shorelines of an ancient mega lake (Figure 11). Hydrologic modeling of the lake's basin showed that at its maximum extent, the lake had occupied an area of about 30,750 square kilometers and would have contained approximately 2530 cubic kilometers of water when filled (Ghoneim and

THE MIDDLE EAST NORTH AFRICA LAND DATA ASSIMILATION SYSTEM – MENA LDAS

Rachael A. McDonnell

The importance of good data for sound decision making cannot be over-emphasized. In water, an understanding of rates and magnitudes of a number of components within any water balance, under various climatic conditions, is needed for sustainable and efficient water policy development and management. Within the MENA region, whilst there are some data on meteorological variables and surface and groundwater flows, in many countries important data on other key components are either not available or are patchy in time and space coverage. Understanding the dynamics of water use and consumption tends to be limited but is important for many different stakeholders.

To help overcome this problem the National Aeronautics

TABLE B1 THE INPUT DATA AND POSSIBLE OUTPUTS FROM THE MENA-LDAS SYSTEM

Static parameters	Meteorological Forcing Fields	State observations	Sample LDAS outputs
- Elevation	- Precipitation	- Vegetation coverage	- Water balances
- Vegetation/land use type	- Downward radiation	- Snow coverage	- Crop types and land use maps
- Vegetation height	- Air temperature	- Surface soil moisture	- Water consumption by crops and vegetation
- Leaf Area Index	- Specific humidity	- Terrestrial water storage	- Monitoring of reservoir level and - groundwater table fluctuations
- Surface Roughness	- Wind speed and direction	- Surface temperature	- Surface and groundwater flows
- Root density and depth	- Surface pressure		
- Soil texture			
- Surface albedo			
- Thermal inertia			
- Emissivity			

FIGURE B1 GENERATED PRECIPITATION FROM SATELLITE SENSORS FOR INPUT INTO MENA-LDAS MODEL

El-Baz, 2007b). The enormity of the lake size and the topographic setting of the area suggested that this lake was formed in the Pleistocene wet epochs when rain was plentiful over a protracted period of time.

In the Holocene time, the area experienced frequent wet episodes, but of less rainfall in comparison to the Pleistocene time, and only the central part of the so-called "North Darfur Mega Lake" was inundated with freshwater.

FIGURE B2 THE WATER CYCLE

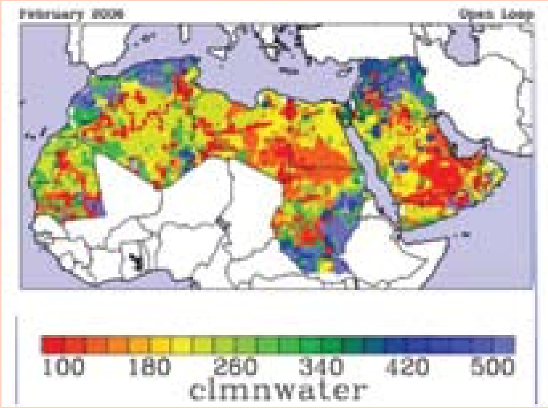
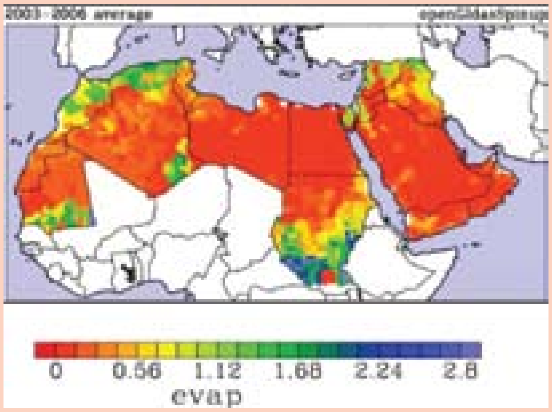


FIGURE B3 THE WATER CYCLE



and Space Administration (NASA) Goddard Space Flight Centre (GSFC), funded by USAID, have developed a regionally specific Land Data Assimilation System (LDAS) model. This complex set of computer programs uses mathematical equations to define the natural processes of water storage and flow, and models have already developed for the regions of North America, South America, and Europe. The modeling system uses NASA satellite data, field observations from MENA countries, and publicly available meteorological analyses from various international research groups. MENA LDAS is particularly useful for the region as it integrates observations from many different sources and is capable of generating data where there are no ground observation points. Special mathematical algorithms in modeling ensure that generated data is rooted firmly to the observed record where it does exist, to limit any errors and inaccuracies.

The data used in modeling are given in Table B1 with a sample input precipitation data set for the region given in Figure B1.

The model will provide estimates of hydrological conditions and flows relevant to water resource management across the region. It will generate times series of maps for important variables such as groundwater fluctuations and storage, soil moisture, surface temperatures, water consumption by crops and vegetation, river runoff, and snow water storage. Sample outputs are given in Figure B2 and Figure B3. Given the frequent measurements of data of certain key meteorological variables, it will also be possible to provide near-real time monitoring of key hydrological processes.

The initial hub for the MENA-LDAS is being developed at the International Centre for Biosaline Agriculture in Dubai and the focus of the research activities there will be to generate regional datasets which will be made available to water managers and decision-makers through a web portal. In addition, capabilities will be developed at a number of national remote sensing centres within the region whose modeling work will focus on water problems that are particularly important to their countries.

With the development of these capabilities, regional capacities for further research will be enhanced. This research will focus on predicting future water flows and uses based on estimated dynamics in the region of environmental, climate, economic, and social changes. These forecasting capabilities will be able to help decision-makers consider the adaptation policies and initiatives needed to face any future water and food security challenges.

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The remnants of the Holocene lake deposits scattered in the central lake area and its oases were preciously identified (Haynes, 1985; Haynes and Mead, 1987; Haynes et al., 1979 and 1989; Pachur and Hoelzmann 1991; Pachur and Rottingen, 1997, Pachur and Wunnemann, 1996: Hoelzmann et al. 2001).

During the residence time of the water in the northern Darfur depression, for thousands of years, much of the water would have seeped into the substrate. This seepage would occur through the primary porosity of the underlying sandstone and/or the secondary porosity caused by fractures in the rock. As observed in the Radarsat-1 data, a nearly continuous segment of about 48 km long is well preserved in the northeastern corner of the lake.

This segment is an intact line zone of about 1 km wide. This zone contains four parallel horizontal markers of former shorelines, which demarcate distinct phases and indicate different stages of lake regression. Since they are characterized by dark signals in the radar images, these strandlines are most likely composed of relatively fine-grained sediments.

The shorelines suggest that the lake level was stable for extended periods. The area, where the shoreline segment is located, is characterized by a complex pattern of semi-active chevron-shaped laminated sand dunes (Haynes 1985). In addition to the shoreline zone, several small wadis in the Radarsat-1 data disappear where they join the shoreline zone, which suggests a channel profile adjustment at this particular lake level. Breaching the outer strandlines while the inner remained intact established that the surface runoff became weaker and small wadis could not be maintained to reach the lake as larger wadis did (Ghoneim and El-Baz, 2007b).

On the northeast edge of the lake depression, another well-preserved segment of shoreline, at the same level (573 m above sea level) with a spit-like feature, was detected in both the SRTM and Radarsat-1 data (Ghoneim and El-Baz, 2007a and b). This arch-like segment measured 20 km in length, 1 km in width, and about 3–5 m in height. The parallel barriers characterizing this segment suggested that the ancient lake was stable long enough at this level. The extension of this shoreline at the opposite, western side, could be clearly traced in all examined data.

Upon completion of mapping of the lake boundaries by the space data and publication of the results, the author conveyed the outcome to officials of the government of Sudan, including the President of Sudan and the Minister of Irrigation and Water Resources. These officials adopted the initiative of "1,000 Wells for Darfur." The same was done in North Darfur, where local officials welcomed the scientific findings.

These developments were welcomed by the United Nations. The UN recognized the importance of the scientific analysis and the well site selection process. Efforts are being made to place the 1,000 Wells initiative under the auspices of the UN to assure both expediency and accountability. These wells need to be sited within reach of the highly populated areas of Darfur farther south of the ancient lake.

This is possible because yearly rainfall during the monsoon season replenishes the groundwater through numerous channels along the slopes of Jabal Marra. At the present time, Boston University team members are utilizing all available space data to select the best sites for well drilling in search of new water resources. In the final analysis, the planned well drilling program is a tangible illustration of using advanced space technology to resolve a problem of water shortage and alleviate a humanitarian crisis.

Empty Quarter (Arabian Peninsula)

The Arabian Peninsula is a vast desert separated from the Great Sahara of North Africa by the Red Sea. High mountain ranges bound it from the west and south. These highlands gently grade into a low area in the central-south part of the peninsula. It is within this depression that the endless dunes of the Empty Quarter reside (El-Baz, 1998b). Like the case of western Egypt, the Empty Quarter includes nearly every type of dune form: linear, crescent and star dunes.

North of the Empty Quarter, there exists a perfect example of the concentration of groundwater by fractures. In this case, the fault zone traces the pathway of two former rivers. The one in the west begins with an intricate tree-branch-like pattern of drainage in the Hejaz Mountains that lead to singular channel, Wadi Al Rummah. After an area that had long been covered by avalanches of wind blown sand, another straight segment of a valley emerges from beneath the sands: Wadi Al Batin. The two wadis must have been connected (Figure 12) to form a single system in the past (El-Baz, 1998a).

The area between the courses of the two dry river courses was highly faulted and fractured. It is believed to have been a major source of the groundwater aquifers in Al Qaseem region of central Arabia. In this region numerous wells were drilled down to depths of over a kilometer. Pumping escalated at these wheat farms for over two decades, at very high rates. Soon the level of the aquifer fell to dangerous levels and many of the farms were abandoned.

However, just like the case of the ancient river course that led to the Kufra Oasis of southeast Libya, these wadis defined the locations of three oases towns: Burayda, Uneizah and Hafr Al-Batin (Figure 12). This became an important component of the proof that surface of the State of Kuwait was a delta of the former river that drained the Hijaz Mountains 850 km west of the Arabian Gulf coast (El-Baz, 1998a). This theory was further developed by additional proof from ground based data on the surface of Kuwait (El-Baz and Al-Sarawy (1996).

The fact that rivers used to cross the Arabian Peninsula was later proven by the SRTM data from the Space Shuttle mission. The topographic data showed numerous courses of former rivers that led to the depression, which enclosed the Empty Quarter dunes. It is believed that such wadis represented defunct rivers, which provided a great deal of water to the depression that is occupied by the dune filed. It follows that the substrate of the Empty Quarter dunes would contain the largest accumulation of groundwater in the Arabian Peninsula. It must be stated that all oil wells drilled in the Empty Quarter have encountered water at numerous depth and with varying degrees of salinity.

Wahiba Sands Basin (Eastern Oman)

The Wahiba Sands are rope-like accumulations of particulate matter within a pear-shaped depression along the eastern coast of the Sultanate of Oman. It was studied by the Boston University research team in the course of evaluating the groundwater potential of the country.

The effects of surface drainage and old channels in the development of the Wahiba Sands are clearly displayed in satellite image data. Radar images revealed several palaeo-channels and associated structures. The southeastward extension of fracture lines from the highlands to the north of the Wahiba basin reaches the southwestern termination of the High Sands. It appeared that continued fluvial erosion of the structurally controlled system was the major

FIGURE 12 THE "ARABIA RIVER" MAPPED BY SATELLITE IMAGES

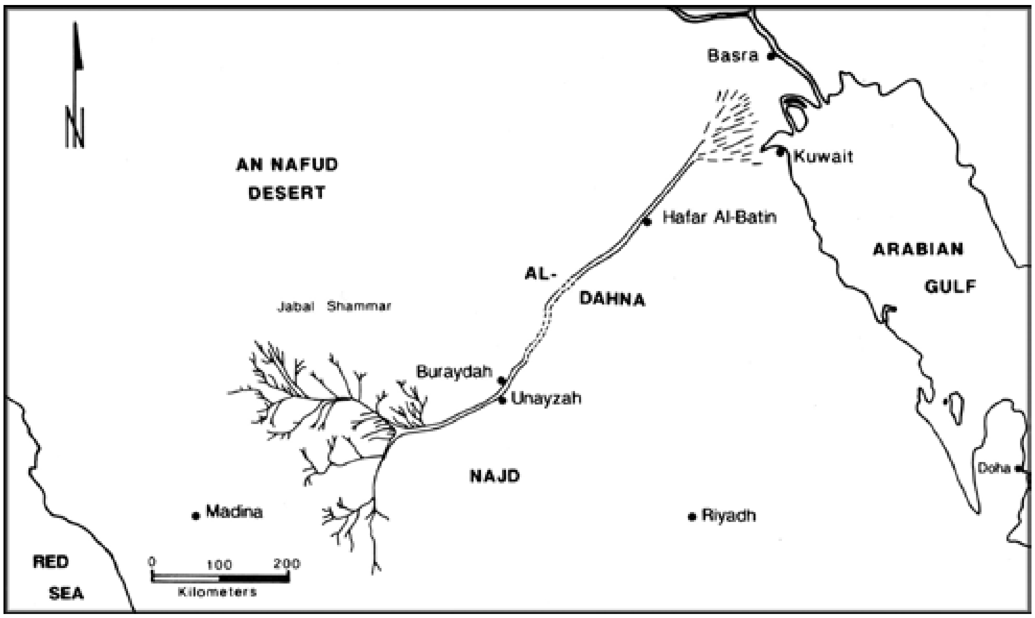
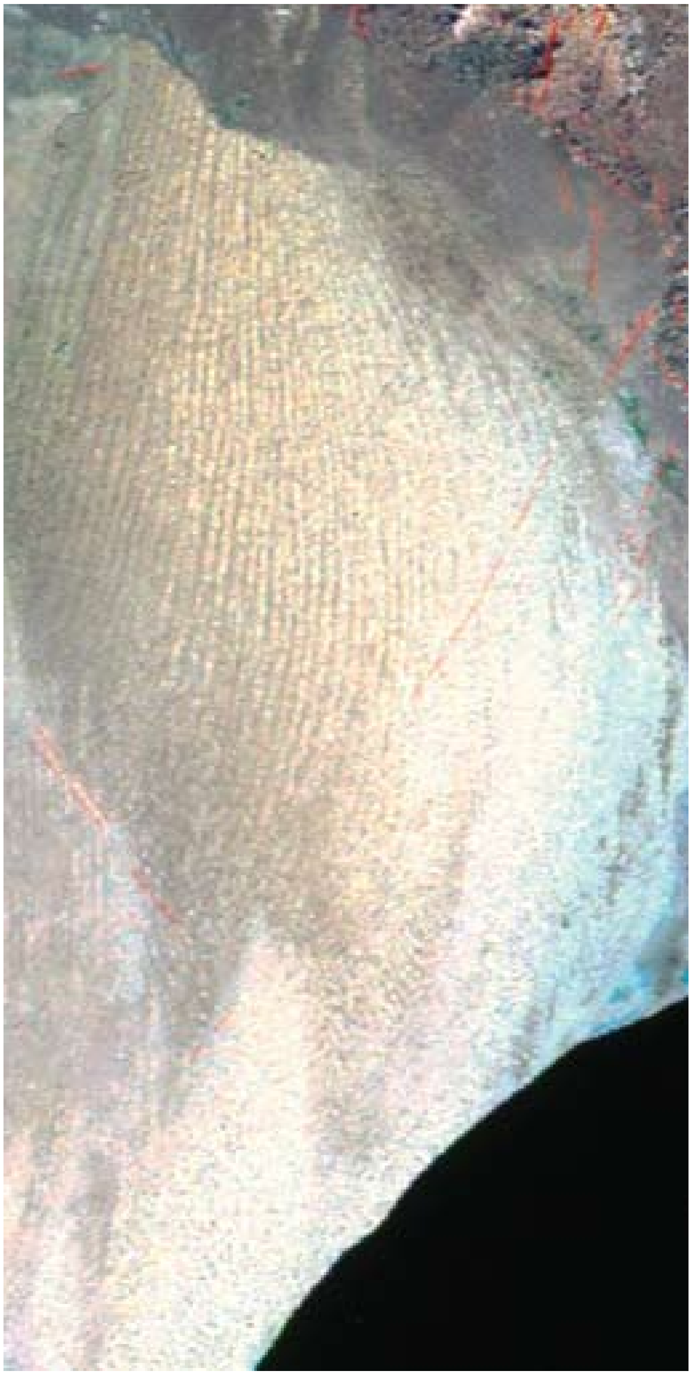


FIGURE 13 WAHIBA SANDS OF OMAN



cause of the linearity of the southwestern edge of the large dunes. This is reminiscent of other locations, where dune terminations are caused by channel truncations. Similarly, the fault and wadi zones caused the linearity of northeastern margins of the Wahiba Sands (Figure 13).

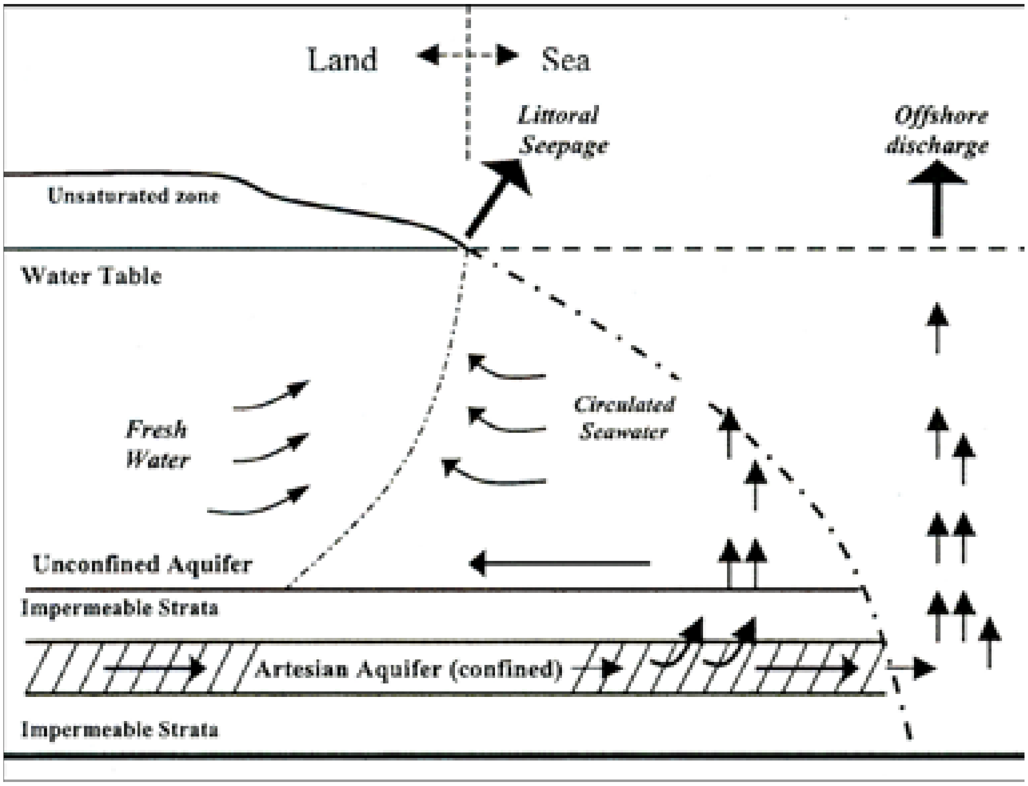
The regional view suggests that structurally controlled fluvial systems, dominant during humid phases of climate, laid down much of the original material of the Wahiba Sands at the mouths of the drainage features. This was also responsible for the extensive volumes of groundwater discharged into the Wahiba basin. Based on these observations, a 100m thick aquifer straddling 1000km2 has been discovered, which holds approximately 12 billion m3 of groundwater.

Once the climate changed and dry conditions prevailed, the wind became the principal surface modification agent. It sorted and shaped the water-deposited sand into the dune and sand fields that form today's features, a sequence of events similar to those observed in the Selima Sand Sheet in the eastern Sahara (El-Baz, 1988, 1998a and b, 2000). As is the case in the eastern Sahara, and other arid regions, the change from wet to dry conditions was not simple, with periods of aridity and enhanced wind activity alternating with wetter intervals from at least Tertiary times until the early Holocene.

The thickness of the Wahiba Sands reflects the depth of the basin. The center of the basin is filled with the thickest deposits of the High Sands and hosts the greatest groundwater concentrations. The southern reaches are filled with less sand. The sand thickness is easy to understand when its fluvial origin is considered. The southeast trending, structurally controlled wadis from the Hajar Mountains (observed in both landsat and radar images) are the dominant fluvial trend that provided much of the sand that filled the basin. The wadis would have supplied material to the north to produce the aeolianite that extends offshore; the aeolianite and the sand ridges are rich in carbonates.

It is suggested that the aeolianite may have formed from calcareous lake sediment that mobilized the carbonate and caused cementation of sand deposits at depth. Upper deposits of the same material would have remained loose, leaving them vulnerable to wind action during the dry climates. The more mature, quartz-rich sand that exists in the south can be explained by the greater distance the sand had to travel from the northern mountains (the principal supplier of the sand). Greater transit distance

FIGURE 14 SCHEMATIC OF FRESH WATER SEEPS ALONG COASTAL ZONES



allows more of the carbonate component to dissolve.

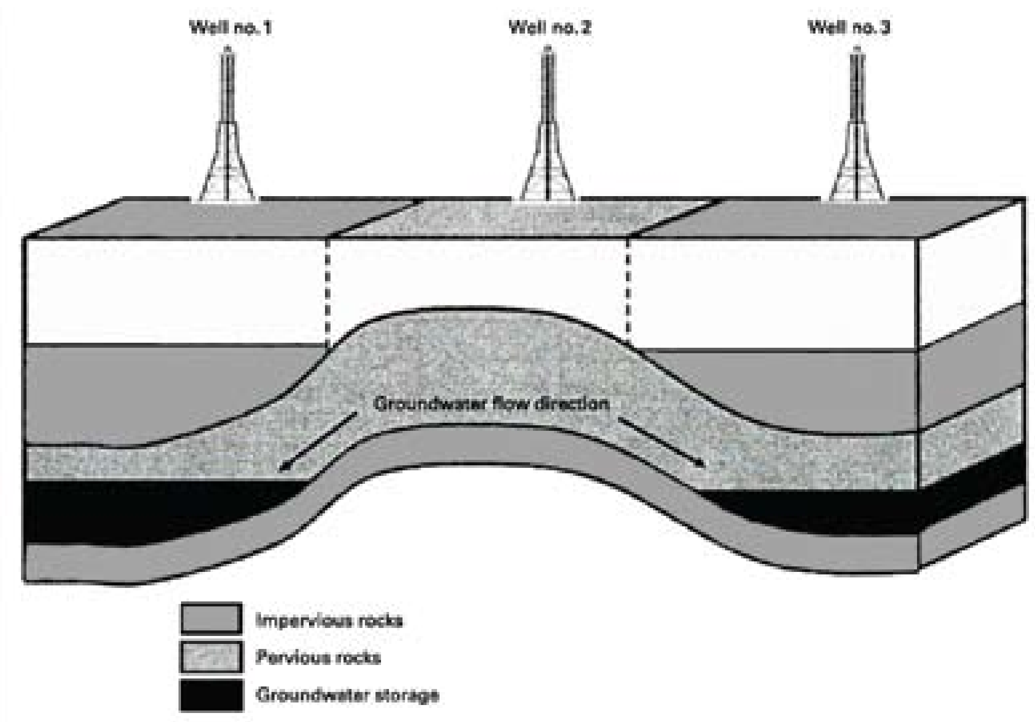
This correlation of the dominant sand composition to the surrounding rocks is also clear in the Selima Sand Sheet of southwest Egypt (El-Baz, 1998b). In the latter case, the sand is quartz rich as would be expected if it had originated from the Nubian Sandstone rocks that exist beneath and to the west of the Selima Sand Sheet, compared with limestone rocks to the northeast. This is consistent with a fluvial system working eastward and northward (as observed from palaeo-drainage directions; Robinson et al., 1999 and 2000) during humid phases of climate, followed by a north–south wind system that continues to dominate to this day (El-Baz et al, 2000).

Thus, remote sensing observations suggest that the Wahiba basin encloses vast groundwater resources. It is a smaller version of the sand-filled depressions of the eastern Sahara (the largest known fresh-water mass in the world; El-Baz, 1998b). The situation is similar to the cases of sandy deserts in the Rajasthan of NW India, the Simpson of Australia and the Taklimakan of China (El-Baz, 1998a). It appears, therefore, that accumulations of large amounts of surface sands in present-day dry areas may be surface indications of the presence of groundwater.

Eastern Mediterranean (Lebanon)

Passage of groundwater within fracture zones has been confirmed in numerous areas. Movement of water within fractures has been established as a potential mechanism for water accumulation in large quantities (El-Baz and Bisson, 1987; NRC, 1996). Furthermore, water runoff into the sea should receive much attention along the coastal zones in the Arab region. Discharged freshwater into the sea occurs either as direct surface runoff (i.e., from rivers and streams), or as groundwater discharge, which is commonly called “submarine springs” and sometime as “invisible rivers”. The Eastern Mediterranean is a typical example of this hydrologic phenomenon,

FIGURE 15 LOCALIZATION OF GROUNDWATER BY SUBSURFACE STRUCTURE WHERE ONE DRY WELL COULD LIE BETWEEN TWO PRODUCTIVE ONES



particularly off the coast of Lebanon (Shaban et al,. 2005).

High precipitation rates (averaging 950-1100 mm) in the region result in large amounts of surface water that rapidly flows toward the sea due to the steepness of the terrain. In addition, groundwater seeps from coastal aquifers to the sea along the bedding planes of rocks (Figure 14) as well as the numerous fracture systems, which increase the flow of groundwater seaward (Shaban et al., 2007).

In Lebanon, there are fourteen small rivers. Three of these are inner ones and originate from the Bekaa plain, which is a depression located between two major mountain chains. The coastal rivers flow directly to the Mediterranean Sea. Recently, remote sensing techniques have been utilized in hydrological studies of the region. As in the aforementioned case of the U.A.E. (Figure 6), MODIS-Terra and TRMM data were used due to their daily acquisition, which permits repeated monitoring. This approach, if improved, can replace instrumentation techniques, because of low cost and high reliability.

The coastal zone of Lebanon is ideal for such an application, because it encompasses a number of issuing rivers and a variety of climatic conditions. Meanwhile gauging stations and hydrographs are lacking or insufficient. Rainfall in this zone is characterized by high rate and frequency of precipitation peaks. The highland slopes (75-100 m/km) as well as the shortness of rivers (less than 50km) create a high flow energy of water toward the sea. The time is often less than 5 hours. This is reflected by low values of lag time of 2.4 on average (Shaban et al., 2005 and 2007).

The high flow energy of running water from the coastal rivers of Lebanon is tempered by the fracture systems and karst conduits, as well as the high meandering ratio of river courses. The huge loss of freshwater from rivers in this hydrologic regime suggests an urgent need to implement surface water harvesting in the region. In addition, damming of the river channels for water harvesting would increase the stay time of water on the surface for replenishment of the various groundwater aquifers in the region.

In addition, it is important to take into account the effects of subsurface structure on the localization of groundwater. Subsurface irregularities due to folding and faulting of strata result in confining the water in certain locations. In such cases, a well dug between two productive ones might turn out to be dry (Figure 15). Thus, knowledge of the geologic structure of a given region is essential for groundwater exploration.

VII. CONCLUSION

Groundwater constitutes one of the most precious resources in the Arab countries. Because of the high aridity and the scarcity of rainfall, it is erroneously perceived that groundwater is scarce or has been depleted in much of the Arab region. In reality, vast tracts in the region have not been explored for their groundwater potential. This includes the extensive, sand covered plains of the Great Sahara and the Empty Quarter. The reason for this is the recent realization that these Arabian sands were rounded, transported and deposited by running surface water during humid climates. The latter alternated with dry phases in the geological past. The last of the wet phases ended about 5,000 years ago. During dry phases, like the present one, the wind acts on the sand deposits to shape desert dunes.

Satellite image data are ideal for investigations of the probability of groundwater concentration in the Arab desert. These data include: (1) multispectral images that clearly depict the surface features and allow the deduction of their geologic history; (2) thermal images that show the location of rain water accumulation just below the surface, which may replenish groundwater aquifers, as well as seepage of groundwater into the sea along coastal zones; (3) radar data that penetrate the sand cover to reveal the underlying topography; and (4) elevation data that depict the direction of surface water flow in the past as well as in the present. Correlations of such data in a GIS allow defining the best way to locate and utilize the groundwater resources.

This contribution exemplifies the use of such data to locate previously unknown groundwater potentials in the eastern Sahara. Two vast ancient lakes were identified in southwest Egypt and northwest Sudan. Furthermore, two ancient river channels were revealed as the cause of the Kufra Oasis and its groundwater resources in southeast Libya. Similarly, the Empty Quarter region of central Arabia and the Wahiba region in eastern Oman were identified as sites of a potential accumulation of vast amounts of groundwater. Some of this water seeps into the sea through fractures beneath the surface.

Based on the results, it is here proposed to initiate a major study of the Arab region with the purpose of identifying regions of potential groundwater accumulation. All available data must be collected for each country or region; using partial data only might be misleading. The data should be processed, analyzed, correlated and updated in an active GIS database. In adjacent countries, such a database should be freely exchanged for planning equitable use of the groundwater resources. This endeavor should be considered of high priority to utilize this valuable resource for the benefit of the Arab people.

For this to be done right, we must adopt a new approach that is distinct from the usual way of doing things. Adherence to outdated theories about groundwater in the Arab region would limit our benefits from this vital resource. We must accept new ideas while applying sound theory to test new propositions along the way. We must be passionate about learning, willing to challenge accepted theories, and able to experiment and test in order to create new knowledge. The created knowledge would allow us to use our resources soundly and efficiently, without harming the environment.

It is evident that much of the Arab region remains not fully charted with regard to groundwater resources. The voluminous literature on groundwater in the region indicates that: (a) current water scarcity will be further exacerbated by rapid population growth and climate change; (b) productive aquifers are being over-drilled and over-pumped with little regulation to assure their sustainability; (c) aquifers shared by multiple nations have not been quantified for equitable use; and (d) vast areas of the Arab deserts have not yet been studied or explored.

These critical issues belong to the policy domain, where government bodies must collect and analyze the required data to regulate groundwater use. It is also essential that attention of policy makers should be sustained in the long term. For this reason, it is instructive to consider major issues that require institutional regulation by policy makers.

Policy Considerations

For presently exploited groundwater resources, it is essential to build a complete digital database. Such a database should be regularly updated based on new findings or more advanced analysis and modeling methodologies. The data collection is required for all regions where water might be extracted for human consumption, agriculture or industrial uses. The required data include geo-coded locations of the wells, their depth and type of host rock; water salinity; and pumping rates, along with historical illustrations of changes to water levels in space and time.

All such data are essential for the proper assessment of the actively mined resources and the establishment of a proper water extraction rate to assure the longevity of a given aquifer. A glaring example of over-pumping with little or no regulation is that of Al Qaseem region in central Saudi Arabia. The unregulated extraction of groundwater for wheat production resulted in exhausting the resource and the abandonment of numerous fields.

With regard to shared groundwater aquifers that extend beyond national boundaries, a database is required for equitable use of the resource. The case studies listed above illustrate that several areas enclose aquifers that lie across national boundaries. The major shared groundwater aquifers in the Arab region include the Selima basin of Egypt and Sudan; the Siwa-Jaghboub region of Egypt and Libya; the Tabuk fracture zone aquifer of Jordan and Saudi Arabia; the Hamad basin of Syria, Jordan, Palestine and Israel; and the eastern Mediterranean mountain region of Lebanon and Syria. It is advisable to collect the necessary information now to avoid potential problems when the available resources will be insufficient to satisfy future needs. In this case, policy regulations and governance need to be inter-governmental.

The next important case for the need of data collection, analysis and clear regulation is that of potential resources in the open desert. As discussed earlier in this contribution, there are vast expanses of land that have not been explored. Basic questions to be answered by exploration - and observation - wells in these cases include the following:

1. What are the boundaries of each groundwater basin or aquifer?
2. How far down is the groundwater level(s)?
3. What is the salinity of the aquifer(s)?
4. How much water is contained in each basin?
5. What are the safe pumping rates that would assure sustainability?
6. Would the water be used for in situ agriculture, or transported to where populations reside (as in the case of the Great Man Made River Project of Libya)?

In this specific case of groundwater in desert basins, it is essential for regulators to consider that such resources are "fossil water." As clearly explained in this contribution, water had accumulated during wet climate episodes that lasted for thousands of years in the geological past. Replenishment may occur in minor locations along the few mountain ranges, while the open desert very rarely receives any rainfall to replenish the groundwater below. From a policy and regulatory perspective, this groundwater must be considered a finite resource that will run out after a given period of time.

In summary, groundwater resources in the Arab region require detailed study and data collection using advanced methodologies, which have been tested and proven in other parts of the world. It is also evident that the use of groundwater requires better and more thoughtful regulations. Neither of these two objectives would be accomplished without sustained attention by policy makers, with emphasis on the long term. Throughout the region, concerted efforts and plans are required at the present time to ameliorate the impacts of water shortages in the future.

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