Exploration of Groundwater in Saudi Arabia

Dr. Amartya Kumar Bhattacharya
BCE (Hons.) (Jadavpur), MTech (Civil) (IIT Kharagpur), PhD (Civil) (IIT Kharagpur), Cert.MTERM (AIT Bangkok), CEng(I), FIE, FACCE(I), FISH, FIWRS, FIPHE, FIAH, FAE, MIGS, MIGS – Kolkata Chapter, MIGS – Chennai Chapter, MISTE, MAHI, MISCA, MIAHS, MISTAM, MNSFMFP, MIIBE, MICI, MIEES, MCITP, MISRS, MISRMTT, MAGGS, MCSI, MIAENG, MMBSI, MBMSM
Chairman and Managing Director,
MultiSpectra Consultants,
23, Biplabi Ambika Chakraborty Sarani,
Kolkata – 700029, West Bengal, INDIA.
E-mail: dramartyakumar@gmail.com
Website: https://multispectraconsultants.com

Abstract

This paper describes an integrated approach to develop of ideal set of tools (methods) for groundwater exploration in arid and semi-arid regions. However, this concept needs to be tested and refined in order to determine the accuracy of the methods for various types of terrain in arid and semi-arid. This paper is suggesting to use remotely sensed data to produce the primary databases that provide various geologic and biologic clues to the presence of near-surface groundwater resources because many of the terrain elements or characteristics that have been shown useful for groundwater exploration are best detected and mapped using remotely sensed image data. Satellite image data not only provide large-area coverage at a reasonable cost, but also provide the means (1) to perform detailed mapping of surface composition and particle size, vegetation, topography, and tectonics; (2) to map the morphology of consolidated surfaces that are covered with dry, unconsolidated alluvium and aeolian sand to depths of 3 meters; and (3) to detect the dielectric and thermal signatures of subsurface water. This method should also incorporates the power of Geographic Information Systems (GIS) in the implementation, testing, and refinement for any groundwater exploration model, which operates on different ground databases to determine locations with higher probabilities for groundwater accumulation. Therefore, this proposed methods/tools is to determine the feasibility of using a GIS/remote-sensing approach for groundwater exploration in two common types of terrain in arid and semi-arid regions.

Keywords: Remote Sensing, GIS, Groundwater.

Introduction

Arid and semi-arid regions are continuously looking for new sources of potable water to help its population, local livestock, and agricultural industries. In order to allow their population to exist within various regions of the country and to allow food production near these discrete and scattered population sites, it is necessary to have local sources of potable water. Within arid and most semi-arid regions, the primary source for potable water is subsurface groundwater. The location of groundwater resources are, therefore, not obvious and the sources have to be identified from particular terrain characteristics that have been shown to be indicative of or conducive to the localisation (entrapment) of meteoric water. Because of the aeolian cover conventional groundwater, exploration often involves geophysical surveys and/or girded exploratory drilling programmes, of both which are expensive and time consuming. It would therefore be beneficial to develop a groundwater exploration method (tool) that is more cost effective and considers large areas of geologically diverse terrain, much of which is covered by eolian deposits.

Therefore, these methods would be useful for unconsolidated aquifers, primarily because they can be tapped at relatively shallow levels using relatively rudimentary methods, but also because remote-sensing data that allows inexpensive, regional analyses can detect the terrain attributes associated with shallow groundwater resources better than those associated with the much deeper sources. In general, unconsolidated aquifers are of two types: alluvial and fracture filling. The first type is represented by alluvial deposits of various ages of deposition that possess the favourable properties of aqueous reservoirs, i.e., interstitial porosity and intergranular permeability. Important examples include valley fill and ephemeral stream (wadi) alluvium. Weathered fracture and fault zones in bedrock represent the second type of unconsolidated aquifer. Such features form conduits through which groundwater can move and be extracted because of secondary porosity and fracture permeability. Both types of unconsolidated aquifers are underlain by some type of confining bed (e.g., aquiclude, aquifuge, aquitard), and recharge is from meteoric water. Some of these aquifers are deeper than others; but in general, fracture-filling aquifers are deeper than the alluvial aquifers. The deeper reservoirs provide larger and longer lasting resources, but their discovery also involves more inference, and therefore, lowers prediction accuracy. Being able to identify (in a probabilistic sense) sites of potential unconsolidated aquifers would be especially important for remote (rural) habitations because the water supply in such aquifers can often be reached by shallow wells at depths less than 30 meters. Such wells can be constructed by digging, boring, driving, and jetting with unsophisticated equipment that does not require skilled operators. In addition, inexpensive pumps, with low operating costs, can be used because of the small vertical lifts involved.

Methods and Results

The main objectives for this method are listed below:

1. Explain the importance of remote sensing technology to produce the best (most direct) results for the detection and mapping of the terrain elements that are indicative of groundwater resources. This should be performed on selected satellite image data (Landsat Enhanced Thematic Mapper Plus [ETM+], Multispectral Thermal Imager [MTI], Shuttle Imaging Radar [SIR], Japanese Earth Resources Satellite [JERS] radar, and Radarsat.) that have the highest likelihood of detecting these terrain elements.
2. Explain the Production of vector, point, and raster databases of the terrain elements that are indicative of groundwater resources, including digital elevation model (DEM) data, well data, and geophysical survey data where available, in a form that is easily imported into the GIS modelling system.

3. Explain the implementation of the logic for the preliminary groundwater exploration model within the GIS environment.
4. Explain how to build a groundwater model using the terrain element databases for two different geologically regions. It is preferable that the iterative modelling process first considers an area or some areas with known groundwater resources and proceeds outward to areas with unknown groundwater resources.

Terrain Elements Indicative of Groundwater: A large number of terrain characteristics to be either indicative of groundwater resources (direct evidence) or conducive geologic settings for trapping groundwater (indirect evidence). The direct evidences should have a higher probability of having trapped groundwater than the indirect evidences and thus these elements should be given higher weighting factors in the exploration model. Only the first two terrain characteristics in the following list are direct evidences, which is the reason why it has been difficult to unambiguously identify sources of groundwater in arid and semi-arid environments. Although most of the individual terrain elements listed below offer diagnostic evidence of favourable subsurface conditions for groundwater occurrence, the spatial coincidence of two or more of these elements can dramatically increase the probability of groundwater localisation. The small number of direct evidences is also the reason why a probabilistic GIS model, which simultaneously examines all of these terrain aspects for a region, is necessary in order to determine the statistical probability of groundwater occurrence at any particular location.

The terrain elements of relevance to groundwater exploration are as follows:
1. Phreatophytic vegetation is the most reliable indicator of groundwater occurrence in arid environments. Phreatophytes are water-loving plants that continuously tap the groundwater supply. Important relations exist between groundwater depth and quality versus vegetation density and type (Meinzer, 1927; Robinson, 1958).
2. Areas of impounded drainage represent fresh-water ephemeral lake deposit that form where episodic stream flow is impeded by natural surface obstructions (e.g., eolian sand deposits, lava-flow lobes). Infiltration dominates over evaporation when the clay content of the sediments is low, enabling fresh-water lenses to form within or beneath the khabras.
3. Igneous dikes act as subterranean dams, causing groundwater ponding on the up-slope gradient of the features.
4. Closed faults can from impermeable barriers or aquicludes to the movement of groundwater underflow (e.g., by development of gouge along the fault plane), causing ponding on the up-slope gradient of the features.
5. Tensional fractures and open faults may possess favourable porosity and permeability properties for storing and transmitting groundwater because of the presence of unconsolidated materials such as colluviums and fault breccias. Areas of fracture or fault intersection are generally, where water circulation is greatest.
6. The contact zone between two rock units may constitute a porous medium, associated with fracturing and weathering processes that could store and transmit groundwater.
7. Inselbergs serve as barriers to both surface and subsurface water flow. Conditions for groundwater occurrence are most favourable in alluvium immediately upslope from an inselberg because of the likelihood of buried bedrock notch or pocket.

8. The crater floors of large maars and tuff rings are attractive sites for localised supplies of groundwater when unconsolidated sediments comprise the vent-fill and the complex does not have subterranean leakage.
9. Playas and sebkhahs identify the lowest portions of closed or semi-closed basins, and the zone immediately surrounding their margins may be a site for a shallow water table, especially if phreatophytes are present; such water, however, may be mineralised.
10. Alluvial fans may hold shallow groundwater along their basal margins, especially when the basal area is comprised of sandy deposits and not highly permeable gravels. The porous, but densely packed sand acts both as a partial barrier to groundwater underflow and as a favourable storage medium. If the sand zone supports phreatophytes, the water table could be especially shallow.
11. Paleo drainage systems that formed during the past humid periods (e.g., late Pliocene and early Pleistocene pluvial) may contain large water-bearing beds that include gravel terraces plus lenses and stringers of porous sand and gravel. Conditions for groundwater occurrence are enhanced if the relic alluvial valleys are still in hydraulic communication with their original catchments areas (underflow recharge).
12. Lava sheets and flows may cover relict stream valleys (sub-basaltic aquifer). When fissured and fractured, the sheets and flows are extremely important for rainfall infiltration to the sub-basaltic aquifer. Favourable sites for groundwater occurrence would be in down-slope wadi segments that emanate from under a sheet or flow front.
13. Deflation hollows are often wind excavated down to the zone of intermittent saturation or the capillary fringe. With the water table essentially at the surface, the hollows often support stands of phreatophytes.
14. Coarse gravel areas along wadi margins are favourable environments for shallow groundwater occurrence as opposed to the present floors, which are normally comprised of fine clastic sediments having a low permeability.
15. Braided stream patterns normally indicate that bed deposits are coarse and, therefore, permeable.
16. Angular or straight wadi channel segments in bedrock areas may indicate fractured or faulted zones containing groundwater.

An additional useful database should be the DEM data for the study areas/region because slope and topography are factors in the movement and localisation of meteoric water. If DEM data do not exist, the data could be produced for specific areas from existing topographic maps (which would be time consuming and expensive), purchased from a commercial database factory (which may also be expensive). The presence and location of each of the above terrain elements should be determined and mapped using appropriate satellite image data. The resulting raster, vector and point databases should then be evaluated spatially and numerically in GIS model to establish probabilities for groundwater occurrence within a region.

The Production of Relevant Terrain Elements from Satellite Image Data: The best image data to detect the terrain are:
(1) Landsat ETM+ data with 6 non-thermal bands at 30-m resolution, a thermal-infrared band at 60-m resolution, and a Panchromatic band at 15-m resolution;

(2) Multispectral Thermal Mapper (MTI) data with 3 visible (VIS) at 5-m resolution and 3 near-infrared (NIR), 4 short-wave infrared (SWIR), 2 mid-infrared (MWIR), and 3 thermal-infrared (TIR) bands at 20-m resolution;
(3) Radarsat Chh data at 10-m or 25-m resolution;
(4) JERS Lhh data at 18-m resolution;
(5) SIR-C L- and C-band data at 25-m resolution.

The optical data require an additional step that removes the atmospheric component from each band's radiance signal so that band image radiance values represent ground radiance. All of the selected image data should then be rectified to the standard map projection while preserving the original spatial resolution of the image data.

The detection of the direct evidences of shallow groundwater (phreatophyte vegetation and standing water or moist ground uses the coincidence of signatures from multiple image data in order to eliminate particular signature ambiguities. The presence of vegetation is often best detected using radar data because even a very small (1 m) stand of vegetation is a good volume scattered of microwave energy, even when the spatial resolution of the radar image is as low as 30 m. Thus, such small vegetation stands appear much brighter than the surrounding ground unless the ground is equally rough. Single polarisation radar data are not however useful for identifying vegetation types, but multispectral optical data can be used for type identification, even though the optical data are integrating both the ground and vegetation signatures within the image pixel area.

Standing water can be confused with shadows in radar and thermal infrared (TIR) data. Shadows and standing water should both appear dark in radar and dark in daytime TIR data, whereas optical data that is atmospherically corrected should have no radiance in any wavelength band for shadows. The visible (VIS) wavelengths bands should have much higher radiance values than the short-wave infrared (SWIR) wavelength bands for standing water (the SWIR radiance values for standing water should be at or very near zero). However, surface materials having clay and carbonate minerals can also produce decreased radiances in SWIR bands relative to those in VIS bands, although the SWIR radiances should not be close to zero. Radar data can provide an indication of water-saturated alluvium because the pore water increases the dielectric properties of the local alluvium relative to the surrounding dry alluvium. Hydrous and carbonate minerals have much higher TIR radiance values than standing water or moist alluvium in daytime TIR image data (and the reverse in night-time TIR data).

Both radar and TIR data are particularly useful in detecting shallow water occurrences in unconsolidated alluvium because they detect reflected or emitted energy differences (anomalies) from subsurface reaches. In such instances, the radar and TIR data should show an anomalously dark area (due to absorption of the microwave signal and due to the colder subsurface water relative to the sunlight surface materials). Thus, individual raster databases should be prepared for the study regions showing the locations of thermal anomalies and of dielectric anomalies; these databases should be used in the proposed GIS groundwater model to increase the probability of groundwater occurrence where anomalies are coincident with any of the terrain elements listed above. In this method, these anomalies should be map in an autonomous manner using the surficial geology map produced from the VIS, NIR, and SWIR bands (all of which are not directly effected by the presence of subsurface moisture) to normalise the radar and TIR data by the average power and thermal radiance of the mapped surface units. In addition, where there are SIR-C image data for the propose study areas with both Lhh and Lvv bands, the empirical relation between band power and soil moisture (Dubois et al., 1995) should be use to derive a soil moisture map for that coverage.

The other main approach is to map the remaining 13 terrain elements generally involves the use of the both optical and radar data, although there are some elements whose mapping is not improved by analysis of a second image database. Elements 3, 6, 7, 8, 9, 12, 13, and 16 are best mapped primarily using the spectral signatures of non-thermal, multispectral optical data. Landsat TM non-thermal optical bands provide very effective discrimination among sedimentary and met sedimentary rock units and eolian units. Reflected optical data are not well suited for discriminating the subtle silicate mineral compositions among the igneous and met igneous rock families. Mapping of many of these terrain elements that involve igneous rocks should be greatly improved by also using the multispectral TIR data provided by the MTI sensor because TIR-band radiance is effected by differences in Si-O bond ratios, unlike any other wavelength region. This is because different silica bond ratios (i.e., different silicate mineral compositions) absorb solar energy (and vibrate causing heat) in different amounts at different TIR wavelengths. The L-band radar (JERS) should also be very useful for extending the mapping of bedrock units in areas where bedrock is partly covered by alluvium and eolian deposits. Mapping of some surficial units that differ in their surface roughness (due to their different weathering properties) may be facilitated by use of radar backscatter data.

The radar image data should be used as the primary database for mapping terrain elements 4, 5, 10, 11, 14, and 15 because these elements are mostly expressions of relief and/or texture and because radar reflections are greatly affected by both of these properties (e.g., Abdelsalam et al., 2000). However, in most of the arid and semi-arid areas, there are certain fault and fracture traces that have little relief or texture and that are manifested mostly by compositional or thermal lineation and, therefore, both the Landsat non-thermal and TIR bands should be examined to detect and map these types of features.

Terrain elements that can be isolated using computer processing (featured extraction) methods should be stored in raster form for input into the GIS modelling system. Many of the elements are better mapped by manual interpretation procedures using the enhanced image data within an GIS (e.g. ARC View) environment because intuitive mental processes can integrate and interpolate both compositional and contextual information simultaneously at faster rate and higher accuracy than existing computer algorithms. The resulting vector and point databases for the terrain elements should then be input into the GIS modelling system for numerical analysis.

GIS Groundwater Exploration Model: the main approach in producing a functional (accurate) model for predicting locations of groundwater occurrence consists of three stages for each of proposed two study regions. Each stage uses a different (but adjoining) sub area of the study region for model testing, verification of results, and model refinement based on the results of the verification process. Each of the three stages involves three steps: (1) GIS analysis of terrain databases for sub area and model prediction of groundwater occurrence; (2) verification of prediction results; and (3) refinement of model logic based on the verification results. Each subsequent stage of analysis within a study region should increase the accuracy of the predictive model.

The sub areas used in the three stages of analysis should be selected based on the distribution of water wells (either currently or previously productive) within a study region, such that the sub areas used in suggested progression from stage 1 to stage 3 should use sub areas with fewer water wells in order to increase the likelihood of undiscovered resources. Thus, the sub area used in the third stage should have the fewest known water wells (possibly no known water wells) and should provide a test of the suggested model for uninhabited areas. Step 2 in stages 1 and 2 should use the locations of water wells as partial verification of the prediction model results. Step 2 in stage 3 should involve field verification of the prediction model results for the third sub area, as well as field verification of particular high-probability predictions within sub areas 1 and 2 that could not be verified with known water well information. Verification should also make use of existing information on where groundwater was not found during previous exploration efforts. This information is as important as the locations where groundwater is or has been present. The verification process needs to also include an evaluation of possible reasons for the occurrence (where it is found) and the non-occurrence (where it is not found) of groundwater so that either the suggested (in this paper) existing terrain elements or model logic can be altered to provide a higher accuracy.

Although well sites that are no longer productive may not provide direct remote-sensing evidences of water (e.g., phreatophytes, TIR and radar anomalies), they should indicate geologic and environmental settings where groundwater did accumulate within a region. Information on both types of well occurrences should also help determine weighting factors for relevant terrain-element databases and to determine if a weighted parametric approach appears to produce more accurate predictions than more simplistic approaches. In any case, the information obtained from the well sites should not preclude the use of other terrain elements in this model because well locations may have been dictated more by accessibility to a source or by discovery techniques than by the mere existence of a source.

There are three fundamental approaches to modeling the occurrence of groundwater: (1) unweighted binary addition of terrain databases; (2) weighted binary addition of terrain databases; and (3) parametric analysis of terrain elements using known groundwater occurrences and application of the resulting parametric equations on terrain databases for unexplored areas to predict new (undiscovered) occurrences. The first approach assumes that all terrain elements are of equal importance in localisation of meteoric water within a region. Thus, each terrain variable is assigned a value of 1 or 0 in a GIS grid cell if it is present or absent, respectively. The analysis is very simple and consists of adding all of the resulting binary terrain databases on a cell-by-cell basis. Those cells with the highest sum values are therefore assumed to have the highest probability for groundwater occurrence. Although extremely simple and rapid to apply, a disadvantage of this approach is that the basic assumption, that the relative importance of all terrain variables is equal, is not true because the direct evidences are obviously more important than the indirect evidences.

The second approach is slightly more advanced than the first approach in that it allows numerical weights to be assigned to particular terrain variables, based on the relative importance of a terrain variable to uniquely identify locations of groundwater. These database weighting factors are multiplied by the binary values of the corresponding terrain databases on a cell-by-cell basis and the database products are then summed to give an overall value for each GIS grid cell. Again, cells with higher sum values are assumed to have higher probabilities for groundwater occurrence. This approach usually produces more accurate results than the first approach on problems that involve natural processes because many geologic processes do not operate in a random manner. The weighting factors used for the terrain parameters than provide direct evidence of groundwater occurrence need to be much larger than the sum values that would result from the co-occurrence of two or three terrain parameters that represent only indirect evidence of groundwater occurrence. Thus, the largest weighting factors should be assigned to the presence of phreatophytes, standing water, and moist (saturated) alluvium. Lower weighting factors should be assigned to less direct evidences such as TIR and radar anomalies, and even lower weighting factors (possibly a value 1.0) should be assigned to the remaining terrain databases that provide even more indirect evidences.

The third approach relies, largely, on training areas or sites where the target material is present. A number of statistical tests are performed on the terrain databases (independent variables) using sites that have and do not have the targeted material. The statistical tests determine the logistical function (equation(s) or set of parametric conditions) that best separate the GIS grid cells into occurrence or non-occurrence of the target material. This approach is widely used in regional assessments for archaeological resources. The approach uses a variety of univariate, multivariate, and multivariate analyses (e.g., discriminant analysis, maximum likelihood, logistic regression) to identify those independent variables and the statistical function(s) that best predict locales with and without the target resource (groundwater in this case). This approach has merit for a regional analysis because there may be a particular subset of a terrain element (such as a particular trending fault set) that is a better conduit or reservoir for groundwater than other aspects of that terrain element. Such subtle (subsurface) differences within particular terrain databases should not easily be detected just using satellite data. Therefore, in this method should explore univariate and multivariate thresholding approaches (based on histogram and scatter-plot distributions and analysis of variance) and alternative multivariate approaches (e.g., discriminant analysis, maximum likelihood, logistic regression), which provide a more rigorous analysis and more constrained results, but each type of statistical analysis has certain strengths and weaknesses (e.g., Kohler and Parker, 1986; Kvamme, 1990).

The Bayesian confusion matrices are recommended for tests of accuracy, which represent populations of predicted versus actual locations of occurrence and non-occurrence of groundwater. Accuracy assessments, should determine those terrain elements or sets of terrain elements that are more reliable indicators of groundwater occurrence within the selected study regions. The field investigations during step 2 of stage 3 for both study regions should involve the following aspects. (1) Determination of groundwater occurrence at locations indicated as having a high probability for groundwater occurrence by proposed model. The locations of unknown existing wells should also be noted, which should be used to refine the exploration model. (2) Notation of surficial cover and distribution at sites with and without groundwater, which may suggest modification of the types of terrain elements being derived and/or of the model, logic being employed. (3) Verification of land-cover databases derived from remote-sensing data and spectral reflectance measurements of surfaces at sites with and without groundwater using a high spectral resolution portable field spectrometer. The spectrometer data may suggest the use of more sophisticated spectral data (e.g., Hyper ion) that include wavelength regions with more indicative spectral signatures for groundwater than those provided by Landsat ETM+.

The smallest ground-cell resolution that should be used for the suggested GIS database analyses is 30 m, based on (1) the average scale of the terrain elements that we are mapping, which is close to that value, and (2) the average scale of all available data, which is also close to 30 m (0.09 ha). This resolution should address both the micro- and macro-environmental factors at site locations. Although this cell size is considered adequate for many other types of regional GIS assessments.

Conclusion

The suggested method and tools will help in the groundwater exploration in arid and semi arid regions. The selected satellite images and image analysis method should help in studying/mapping the ground features. The main goal for the GIS environment is the development of a working system that relies, as much as possible, on the more user-friendly GIS software for display and model analysis of data. The developed system should be able to, display the results derived from a particular model, both in annotated, colour image format and in report format, containing graphical and tabular information from the particular results. The appearance and contents of these items on the display (and for the report) should be interactively adjustable, based on user preference.

References

Abdelsalam, M. G., Robinson, C., El-Baz, F. and Stren, R. J., (2000), Applications of orbital imaging radar for geologic studies in arid regions: The Saharan testimony: Photogrammetric Engineering and Remote Sensing, v. 66, 717-726.

Berlin, G. L., Davis, P.A., and Sheikho, K. M., (1997), Identifying sand-obscured lava flow surfaces with SIR-A image data: Harrat Hutaymah, Saudi Arabia: 12th International Conference of Applied Geologic Remote Sensing, Environmental Research Institute of Michigan, Denver, II-84 - II-90.

Berlin, G. L., Sheikho, K. M., and Al-Naser, A. H., (1988), SIR-B view of the Jabal Hadn lineament and its groundwater implications: Twenty-first International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Ann Arbor, Michigan, 709-720.

Berlin, G. L., Tarabzouni, M. A., Al-Naser, A. H., Sheikho, K. M., and Larsen, R. W., (1986), SIR-B subsurface imaging of a sand-buried landscape: IEEE Transactions on Geosciences and Remote Sensing, v. GE-24, 595-602.

Berlin, G. L., Tarabzouni, M. A., Sheikho, K. M., and Al-Naser, A. H., (1985), SIR-A and Landsat MSS observations of eolian sand deposits on the Al Labbah Plateau, Saudi Arabia:

Nineteenth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, Ann Arbor, Michigan, 311-321.
Davis, P.A., and Berlin, G.L., (1988), Rock discrimination in the complex geologic environment of Jabal Salma, Saudi Arabia, using Landsat Thematic Mapper data: Photogrammetric Engineering and Remote Sensing, v. 55, 1147-1160.
Davis, P.A., and Berlin, G. L., (1997), Discrimination of sedimentary rock units in the Painted Desert, Arizona, using Landsat Thematic Mapper data: 12th International Conference of Applied Geologic Remote Sensing, Environmental Research Institute of Michigan, Denver, I-37.
Davis, P.A., Berlin, G. L., and Sheikho, K. M., (1998), Polarimetric SAR data: A potential for mapping near-surface phosphorite deposits in arid regions: 13th International Conference of Applied Geologic Remote Sensing, Environmental Research Institute of Michigan, Vancouver, B.C., I-245-246.
Davis, P.A., Breed, C.S., McCauley, J.F., and Schaber, G.G., (1993), Surficial geology of the Safsaf region, south-central Egypt, derived from remote sensing and field data: Remote Sensing of Environment, v. 46, 183-203.
Davis, P.A., Mullins, K.F., Berlin, G.L., Al-Farasani, A., and Dini, S.M., (1989), Phosphorite exploration in the Thaniyat and Sanam districts, Kingdom of Saudi Arabia, using Landsat Thematic Mapper data: Seventh Thematic Conference on Remote Sensing for Exploration Geology, Environmental Research Institute of Michigan, Calgary, Alberta, Canada, October 2-6, (1989), 1205-1221.
Dubois, P. C., van Zyl, J., and Engman, T., (1995), Measuring soil moisture with imaging radars: IEEE Transactions on Geosciences and Remote Sensing, v. 33, 915-926.
Pampel, F. C., 2000. Logistic Regression: A Primer. Sage university Papers Series: Quantitative Applications in the Social Sciences, Series Number 01-132 (M. S. Lewis-Beck, Ed.) London: Sage Publications.
Powers, R. W., Rameriz, L. F., Redmond, C. D., and Elberg, E. L., (1966), Geology of the Arabian Peninsula – Sedimentary Geology of Saudi Arabia: Geological Survey Professional Paper 560-D, U.S. Government Printing Office, Washington, D.C., 147 p.
Raghunath, H. M., (1982), Ground Water: John Wiley and Sons, New York, 456 p.
Riddler, G. P., van Eck, M., Aspinall, N. C., McHugh, J. J., Parker, T. W. H., Farasani, A. M., and Dini, S. M., (1986), Sirhan-Turayf phosphate project – As assessment of the phosphate resource potential of the Sirhan-Turayf region: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record RF-TR-06-2, 178 p.
Schaber, G. G., and Breed, C. S., (1999), The importance of SAR wavelength in penetrating blow sand in northern Arizona: Remote Sensing of Environment, v. 69, 87-104.
Schulz, E., and Whitney, J. W., (1986), Vegetation in north-central Saudi Arabia: Journal of Arid Environments, v. 10, 175-186.
Vrabel, J., 1996, Multispectral imagery advanced band sharpening study: Photogrammetric Engineering and Remote Sensing, v. 62, 1075-1083