Chapter 20

Assessment of Groundwater Resources in Water Spring Areas Using Geophysical Methods, Northern UAE

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Abstract The Khatt, Madab, and Al Ghmour Springs are important springs in UAE. They are located in the foothills of the Oman Mountains. The water temperature of these springs is relatively high (approximately 39 °C). Overexploitation of fractured aquifers negatively affected the waterflows from these springs. The outflows from these springs are time-dependent and range from 10 to 50 L/s (until 1998) to 1–10 L/s (until 2010). To assess the current conditions of the spring areas, relevant data were carefully reviewed, analyzed, and stored in a GIS database. A 3D-geological model was developed for the Khatt Springs area, which allowed different types of visualizations, calculations, and predictions. In addition, a 2D earth resistivity imaging survey was performed to evaluate the available groundwater resources, characterize the major faults/fractures feeding these springs, and to determine the locations of saturated fractures and karsts and the thicknesses of the unconsolidated materials in the wadis. Borehole and drilling information from observation wells were utilized to enhance the analysis of the earth resistivity imaging data. The described procedures and acquired results indicated that it was

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possible to determine the locations of two production wells for feeding Al Ghmour Springs with water during drought periods to keep it alive.

Keywords 2D earth resistivity imaging • 3D geological modeling • Khatt Springs • Madab Springs • Al Ghmour Springs • UAE

20.1 Introduction

There are wide applications of surface geophysical methods for studying water resources in arid and semiarid environments. Geophysical methods allow for continuous scanning of subsurface soils and water saturation, which are of high importance in remote arid areas and wadi systems where information and measurements are scarce or absent. To accomplish the same tasks with piezometers, a large number of piezometers would be required because piezometers only allow observations of conditions at discrete points. In addition, individual techniques for estimating water fluxes in unsaturated zones usually have their own limitations.

The conductivity of water, which is an intrinsic property of the total dissolved solids, indicates how well water conducts electricity. For example, the specific conductivity (SC) of a clay-free gravel layer saturated with saline water could be as high as 100 times the SC of the same gravel layer if it were dry (Hermans et al. 2017). This major difference in SC based on the degree of saturation and the water quality makes geophysical methods very useful for tracing groundwater contaminations and saltwater intrusions in clay-free aquifers. The resistivity of fractured rocks is controlled by the secondary porosity and groundwater salinity (Kalisperi et al. 2018; Khalil et al. 2020). The application of electrical methods for groundwater explorations and assessments has the following advantages (Ebraheem et al. 2014a, b).

- Reduced need for borehole drilling and direct sampling of groundwater,
- Uncostly data acquisition for quick monitoring of large areas as well as optimizing the locations of monitoring wells,
- Electrical conductivity/resistivity is controlled by groundwater salinity, which is readily interpreted in terms of groundwater quality.

The Khatt Springs area includes the most prominent springs in UAE and is located at the western piedmont of the Oman Mountains (Fig. 20.1). These springs are recognized by two main parts (the north Khatt and south Khatt), and the flows from these areas were gauged in 1966. The south Khatt Spring flows directly from the limestone hills, while the north Khatt Spring appears approximately 3 m west of the foothills. Several constructions have been implemented to increase the flow from each spring. The Madab and Al Ghmour Springs are located in the eastern foothills of the Oman Mountains (Fig. 20.1). The water of these springs is characterized by relatively high temperatures (approximately 39 °C) compared to the

temperatures of all other existing groundwater (25–32 °C) within the northern emirates that come from the same domain. The temperature of groundwater may be assumed to increase with depth from a level approximately 20 m below ground level at a gradient of approximately 1 °C per 30 m. The difference between the temperatures of the spring waters and those of the groundwater in the surrounding area suggests that the spring waters originate from a considerable depth, perhaps approximately 300 m below the ground level (Halcrow and Partners 1969; IWACO 1986). The water of these springs has been traditionally used for bathing, medication, and irrigation. Since 1979, the Khatt and Madab Springs have gone through further developments and have become major bathing and recreation sites.

Aflaj (plural of Falaj) is an Arabic term that describes a complex man-made network of tunnels composed of vertical shafts that capture groundwater or base flows at the foothills of mountains and direct the water to the land surface by the force of gravity, without any intervention of machines, mainly for irrigation purposes (Alshahrani and Rizk 2020). Aflaj recharge depends on water sources in upstream areas, including groundwater, natural springs, and rainfall (Al Amri et al. 2014). The well locations, channel gradients, aquifer types, and amounts of recharge are the main factors affecting Aflaj discharge rates (Beckers et al. 2013). The climates, geologic settings, and human activities are the main factors affecting the water quality and water use of Aflaj systems (Al Tikriti 2015).

Water outflows from small springs and hand-dug wells are collected in Aflaj. This water is then essentially used for cultivating palm dates and in other market productions. The area of the springs (Ruus Al Jabal Peninsula) consists mainly of highly karstified limestones and dolomites, the thicknesses of which reach 3000 m (Hudson and Chatton 1959). Rainwater percolates through the limestone beds following the joints, fractures, other secondary openings, and the general trend of the folded strata. These strata have north-facing aspect (direction of slope), and the groundwater outflows from these strata emerge through high-level overflow springs, where impermeable rock layers encounter the flow paths of groundwater, or at sea level.

The climate of UAE is generally characterized by hyperarid desert conditions with two main seasons: very hot, sunny summers (May–September, when temperatures often exceed 40 °C) and pleasantly mild, cool winters (October–April, when mean annual average temperatures are approximately 27 °C). Rainfall events are rare and unpredictable with irregular precipitation patterns; however, they occur in the forms of showers or downpours that can sometimes be intense (Tourenq et al. 2011). The mean annual rainfall varies from 150 mm in the mountainous areas to approximately 90 mm on the coast and less than 50 mm in the sandy desert areas.

Due to the drought conditions that prevailed in the period from 1998–2010 and the necessity of intensive groundwater exploitation for irrigation purposes, which has caused severe cones of depression (Fig. 20.2), the outflow from the Khatt Springs was not enough to keep the temperature in the swimming pools at the desired level (Mohamed et al. 2016). The relatively long water residence time in the pools resulted in the deterioration of the environmental conditions in the recreational park around the pools and in the spread of mosquitoes.

Fig. 20.1 Map of the location of the study area showing the surface geology (Source British Geological Survey and Ministry of Energy 2006). The map shows the locations of the cross sections A-A' and B-B' and the 2D earth resistivity profiles

Groundwater levels fluctuate considerably and are controlled by recharge events. The maximum water table increase in this region (approximately 40 m) was observed in March 1997 in well Khat-1 near Khatt Springs (Fig. 20.1).

The impacts of precipitation on fluctuations in the level, flow rate, and temperature of groundwater in the limestone aquifer in the study area have been

Fig. 20.2 Map illustrating the drawdown of up to 65 m that occurred in the period from 1969 to 2005. Major geomorphologic units and agricultural lands are also shown

Table 20.1 Impacts of the 1999–2010 drought on Khatt Springs

North spring situation in the period from 1979 to 1998	North spring situation in the period from 1999 to 2010
Outflow ranged from 10 to 50 l/s	Outflow ranged from 1 to 10 l/s
Rainfall rate ranged from 60 to 360 mm/year	Rainfall rate ranged from 20 to 150 mm/year
Source water temperature ranged from 39 to 40 °C	Source water temperature from 33 to 37 °C
Irrigation Aflaj work without pumping	Irrigation Aflaj only work with pumping from hand-dug wells

intensively studied since the late 1970s and are summarized in Table 20.1. Groundwater depletion in the areas of the Madab and Al Ghmour Springs is severe, to the extent that water has completely ceased to flow from the Al Ghmour Springs. All the available borehole data, drilling information, and environmental data from 1979 to 2015 were reviewed, analyzed, and stored in a GIS database. Then, the spatial analysis GIS algorithm, enhanced with graphic capabilities, was utilized to analyze and reinterpret these data and to preliminarily assess the current conditions of water resources (water availability and management challenges) in the northern part of UAE. The processed results were implemented in the preparation of a complete dataset as inputs to a 3D geological model for the Khatt Springs area. The main objectives of the present study are as follows.

- Determining the geological and hydrogeological setting of the Khatt, Ain Madab, and Al Ghmour Springs areas; emphasis was given to the impacts of geological structures on groundwater accumulation and flow patterns.
- Evaluating the impacts of drought years and groundwater depletion caused by intensive irrigation on the flows and water temperatures of the springs.
- Application of 2D earth resistivity imaging techniques for mapping the karsts and/or fractures feeding the springs.
- Applying developed software for digital 3D geological modeling that utilizes cross section-based networks for subsurface interpolation in heterogeneous aquifers.

20.2 Geological and Hydrogeological Settings

The northern Oman Mountains in the Khatt Springs area are composed of Jurassic to Cretaceous Musandam Group limestones. The western Jiri coastal plain consists of Late Tertiary to recent alluvial sediments overlying the Late Cretaceous Juweiza Formation (BGS and MOE 2006; Halcrow and Partners 1969; Sherif et al. 2006, 2018). The Juweiza Formation is composed of a sequence of marl and shale with

intercalations of debris of basic igneous rocks, chert, and limestone (Fig. 20.1). Two major tectonic events have affected the area. The first was in the age of the Upper Cretaceous, when the Hawasina Formations and the Samail Ophiolite were thrust over the Musandam limestone; then, the Mid-Tertiary, the formation of the Oman Mountains occurred due to folding, faulting, and thrusting (Fig. 20.1). As a result of these major structural events, major northeast-trending anticlinal structures were formed, such as the Hagab Mountains thrust fault along the Musandam Mountains, the Jiri plain, the Dibba zone to the southeast, and the Batha Mahani thrust that runs along the valley of the Wadi Tawiyean (Robertson et al. 1990). Accordingly, the Musandam limestones are strongly faulted (Fig. 20.3), with major trends running northeast (parallel to the Dibba zone thrusts), north, and northwest (parallel to the Wadi Ham system).

The topographic setting and structural pattern generally control the thickness of unconsolidated materials. Several subsurface geological cross sections along different directions were constructed using borehole data and drilling information. Two examples of these cross sections in the areas of the Khatt and Ain Madab Springs are shown in Figs. 20.3 and 20.4, respectively. The Masafi Mountains dominate the upstream part of the east coast area, and alluvial plains prevail in the downstream region, in which the sediments are composed of recent Pleistocene wadi gravels. The alluvium gravel layer overlays the consolidated rocks of the Semail Formation with fractured zones at some locations (Fig. 20.5). The two hydraulically connected groundwater aquifers can be characterized as follows.

Fig. 20.3 A subsurface geological cross section in the east–west direction (Source IWACO 1986). Location of the cross section is shown in Fig. 20.1

Fig. 20.4 A N-S subsurface geological cross section across the Wadi Ham, approximately 3 km from the Gulf of Oman

Quaternary aquifer: This aquifer is composed of gravel plains of recent silts and conglomerates and meets the mountain front at a high angle. This layer overlies the thick Juweiza Formation on the west coast, which is generally characterized by low permeability and thus acts as an aquitard rather than an aquifer (Fig. 20.3). On the east coast, the aquifer overlies the consolidated rocks of the Semail Formation.

Fractured rock aquifer: The area of the fractured rock aquifer refers to the exposed thick karstified limestone of Jurassic–Cretaceous age in the mountains of the Khatt Springs area (Fig. 20.3) and to the fractured Semail Ophiolite in the areas of the Ain Madab and Al Ghmour spring (Fig. 20.4).

The carbonate layers are composed of well-jointed dolomitic limestone and limestone interbedded with calcareous shales. These beds dip at a very high angle, up to 90°, to the west (Fig. 20.3). The ophiolite layer generally dips toward the east and toward the wadi course (Fig. 20.4).

20.3 Digital 3D Geological Modeling

3D geological modeling is a state-of-the-art technique commonly used in the field of economic geology. It is based on statistical or geostatistical interpolations between stratified scattered boreholes. The method is adequate in areas with sufficient borehole data because it leads to reduced heterogeneity and an inadequate loss of the “real-world” settings of lithostratigraphic layers. The complex structural setting of Quaternary sediments cannot be represented correctly by following only the geostatistical approach (Wycisk et al. 2005). Therefore, the first 3D geological model, comprising approximately 2000 km², was developed for the Khatt Springs area based on 39 borehole records. In addition to drilling information, a digital

Fig. 20.5 Hydrogeological map of the northern part of UAE (Source IWACO 1986)

elevation model (DEM), geophysical logging and profiling information, and geological and hydrogeological maps were also used to develop the 3D database. The developed 3D geological model of the Khatt Springs area allowed different types of visualizations, calculations, and predictions within the hydrogeologic model (Fig. 20.6). Digital, subsurface 3D model results are of specific need in simulations of water resource management options.

Fig. 20.6 3D geological model constructed for the Khatt Springs area

20.4 DC Earth Resistivity Method

The DC earth resistivity method measures the electrical resistivity distribution in the subsurface by transmitting a current into the ground using two electrodes (C1 and C2; Fig. 20.7) and subsequently measuring the resulting potential difference between a second pair of electrodes (P1 and P2; Fig. 20.7). The apparent resistivity of the subsurface can be calculated using Ohm's law ($R = \Delta V/I$, where R represents the resistance, ΔV depicts the measured potential difference, and I stands for the injected current). Assuming a homogeneous subsurface, these measurements, which are geometrically corrected, can be recognized as apparent resistivity values rather than true resistivity values.

The measured resistivity values are controlled by the earth resistivity, degree of saturation, and groundwater quality (Cartwright and Sherman 1972; Ebraheem et al. 1990, 1997; Haeni et al. 1992). The resistivity value of a fractured zone is dependent on the degree of rock fracturing and on the groundwater salinity. The 2D DC-resistivity profiling method is conducted by applying several measurements along a profile at different offsets (Fig. 20.7). Memory earth resistivity and IP instruments and a switch box were used for eight channels. The switch box was used to automatically control the distances between electrodes. The profiling data were inverted by using an iterative smoothness-constrained least-squares inversion method (deGroot-Hedlin and Constable 1990; Sasaki 1992; Loke 1997; Aizebeokhai 2010) to create a tomogram-like model of resistivity. Linear zones of low resistivity that were continuous with depth were interpreted as fracture zones.

Fig. 20.7 A pattern of electrode arrays implemented in the DC resistivity method and the associated geometrical factors (a–d) and e the arrangement of the electrodes for a 2D electrical survey and the sequence of measurements used to build up a pseudosection (Source Ebraheem et al. 2014a, b)

20.5 Data Acquisition and Interpretation

20.5.1 Khatt Springs

With the main purpose of determining the depths and extensions of the fracture zones in the carbonate aquifer feeding the Khatt Springs, measurements of six earth

resistivity profiles were conducted in the Khatt Springs area southeast of Ras Al Khaimah City (Fig. 20.1). An example of an interpreted geophysical profile with a total length of 2220 m (profile P-1; Fig. 20.1) is shown in Fig. 20.8; at this profile, it was possible to determine the areas of saturated cavities and fractures in the Musandam limestone. The obtained results were used to design a production well, KP-1, near profile P-1 (Fig. 20.5). The drilling information of this well-confirmed the obtained interpretation results (Ebraheem et al. 2014a, b).

20.5.2 Ain Madab Springs

Three earth resistivity profiles were conducted in the Madab Springs area (Fig. 20.1). The interpreted results indicate the presence of two layers (an example is shown in Fig. 20.9; profile P-2). The upper layer represents saturated alluvial gravel with slightly brackish water. This layer has a true resistivity ranging from 33 to 100 Ω -m and a thickness ranging from less than 50 to 250 m. This layer overlies the ophiolite layer, which has low permeability except in some places where is fractured. The interpretation of this profile was constrained by comparisons with available lithological logs of existing wells (Ebraheem et al. 2012, 2014a, b).

20.5.3 Al Ghmour Springs

The interpreted results of three resistivity profiles located in the Al Ghmour Springs area also indicated the presence of two layers. As in the Ain Madab Springs area, the upper layer has a true resistivity ranging from 33–100 Ω -m and a thickness ranging from 60 to 250 m; this layer probably consists of alluvial gravels saturated with slightly brackish water (an example of profile P-5 is shown in Fig. 20.10). This layer overlies the ophiolite layer, which is generally a low-permeable or impermeable layer except in places where it is fractured.

Fig. 20.8 Results of 2D earth resistivity modeling for Profile P-1 in Khatt, Ras Al Khaimah. See Fig. 20.1 for profile location

Fig. 20.9 Results of 2D earth resistivity modeling for Profile P-2 in Madab, Fujairah. See Fig. 20.1 for profile locations

Fig. 20.10 Results of 2D earth resistivity modeling for Profile P-4 in Al Ghmour, Fujairah using the a dipole-dipole array and b Schlumberger array. See Fig. 20.1 for profile locations

20.6 Conclusion and Recommendation

A GIS-based comprehensive study was conducted to assess the current situation of water springs in UAE. The investigations included field and laboratory components. Based on the results of the study, the following conclusions could be made.

1. The potentials of limestone aquifers to serve as strategic resources are very high. To develop additional production wells, new locations must be predicted by geophysical investigations as well as by optimized location sites, which in turn must be assessed by geological structure analyses of fractured zones within the outcropping limestone formation. The maximization of expected cavity-building as well as the clustering of fractures can be expected at the zones in which structural elements cross inside wadi courses.
2. For a deeper understanding and long-term development in terms of prognoses, ongoing monitoring of the pressure head of the main free-flowing well near Khatt Springs is strongly recommended due to expected interfering hydraulic effects. This monitoring can be done by flow rate measurements and, more importantly, pressure head measurements.
3. The hydrogeological system in the east coast area is composed of two aquifers. The first is the upper Quaternary aquifer, which is composed of wadi gravel and represents the main aquifer. The second is the lower fractured ophiolite aquifer, which has a low groundwater potentiality in general and modest to high groundwater potentiality in the areas that are strongly affected by regional faulting (e.g., the Wadi Ham).
4. It was possible to determine the locations of two production wells in the Wadi Ham and Ain Madab Springs area for feeding the spring with water during times of drought to keep it alive.
5. The rehabilitation of Al Ghmour Springs as a bathing pool looks very promising and can be reasonably realized. To this end, the following topics must be taken into account.
 - The temperature and pH of the springs indicate a fault/fracture-bounded situation at the higher flank of the wadi shoulder.
 - The spring outlet must be traced toward the bedrock/solid rock position of the morphologically incised depression. The spring outlet must be dug as deep as possible into the unweathered solid rock formation to the deepest position of the fall lines of the incised depression at the entry of the contact zone toward the wadi sediments. To avoid losses of spring water, it is recommended that the water is brought by pipe or by the construction of sealed small canals toward the bathing pool.

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