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Preliminary Geophysical Investigation for Suggested Water Harvesting Sites in the Northern Jordanian Badia

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Abstract: In this study, an integration of geophysical survey methods including Vertical Electrical Sounding (VES), ground geo-magnetic methods and soil-samples texture analysis were performed at selected suggested water harvesting sites in the Northern Jordanian Badia to investigate and characterize the shallow subsurface stratigraphic sequences and structures. The preliminary results of geoelectrical investigations provided general picture about the nature of subsurface stratigraphical sequences at each surveyed site. Moreover, the results of ground geo-magnetic investigations indicated to the presence of near-surface subsurface faults that could play a negative role for establishing water harvesting dams at Al-Subhi-1 site and to a lesser extent at Al-Ghulaisi site. The soil textural analysis of Al-Subhi-1 site was found to be of a loamy sand type, whereas the other five sites were found to be of a clayey loam type. However, further high resolution geophysical techniques including the use of low-frequency Ground Penetration Radar (GPR) and 2D-Electrical Resistivity Tomography (ERT) are recommended to conclusively decide if these sites are suitable or not for water harvesting.

Keywords: Badia, geophysical, Jordan, soil, water harvesting

INTRODUCTION

Jordan is located in an arid to semi arid region where around 90% of its land receives an average precipitation of less than 100 mm/year while only 3% of the land receives an average annual precipitation of 300 mm or more (Zeyad *et al*., 2008). Jordan is characterized by severe weather conditions, therefore great temporal and spatial variations in rainfall; runoff and evaporation amounts are expected (Zeyad *et al*., 2008). The annual population growth rate in Jordan is estimated to be around 2.8%. Based on this percentage, it is estimated that the total population in Jordan will be around 10 million by 2020 (Nortcliff *et al*., 2008). This will add more pressures on the existing water resources in the countries leading to a massive decrease in per capita to 90 m^3/capita/year by 2025 (Al-Adamat *et al*., 2010). Water harvesting has been practiced in Jordan throughout history for both irrigation and household purposes. There are indications of early water harvesting structures believed to have been constructed over 9000 years ago in Southern Jordan (Prinz, 1996). In the northeastern of Jordan (Jawa), water was retained by deflection dams 5000 years ago (Abdel Khaleq and Ahmed Alhaj, 2007).

AlAyyash *et al*. (2012), conducted a research project on selected sites for rain water harvesting systems in the Jordanian Badia. In their research, the researcher concluded that these sites have the potential to be utilized for water harvesting based on rainfall, runoff and the catchmnet area for each site. This study aims to conduct a geophysical and soil investigation for the six sites investigated by AlAyyash *et al*. (2012) in order to determine their suitability for water harvesting.

INVESTIGATED SITES

The suggested water harvesting sites are located in the northeastern part of Jordanian badia (Fig. 1a, b) and their geographical coordinates and altitudes are listed in Table 1. Table 2 provides a summary of the major geological formations and lithology that are exposed at and surrounding each of the suggested water harvesting site.

Table 1: Geographical coordinates of the suggested water harvesting sites

Location	N-latitude	E-longitude	Elevation
Al-Subhi site-1	31º 49.580'	37º 30.630'	617.5 m
Al-Subhi site-2	31º 51.272'	37º 40.924'	630.0 m
AlAssra	32º 07.037'	36º 51.340'	778.0 m
Wadi Ali (Al-Abed)	32º 10.294'	37º 01.853'	770.0 m
Al Manareh (Al-Ghuliasi)	32º 07.037'	36º 51.340'	727.0 m
Ghadeer Al-Naqa	32º 15.604'	36º 37.684'	868.0 m

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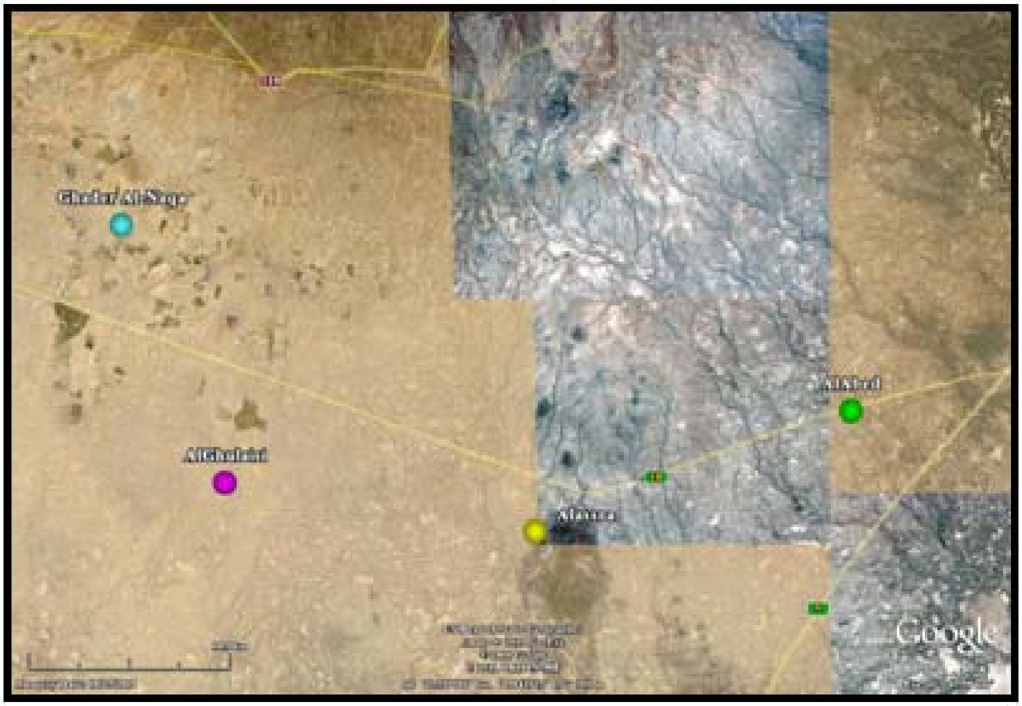
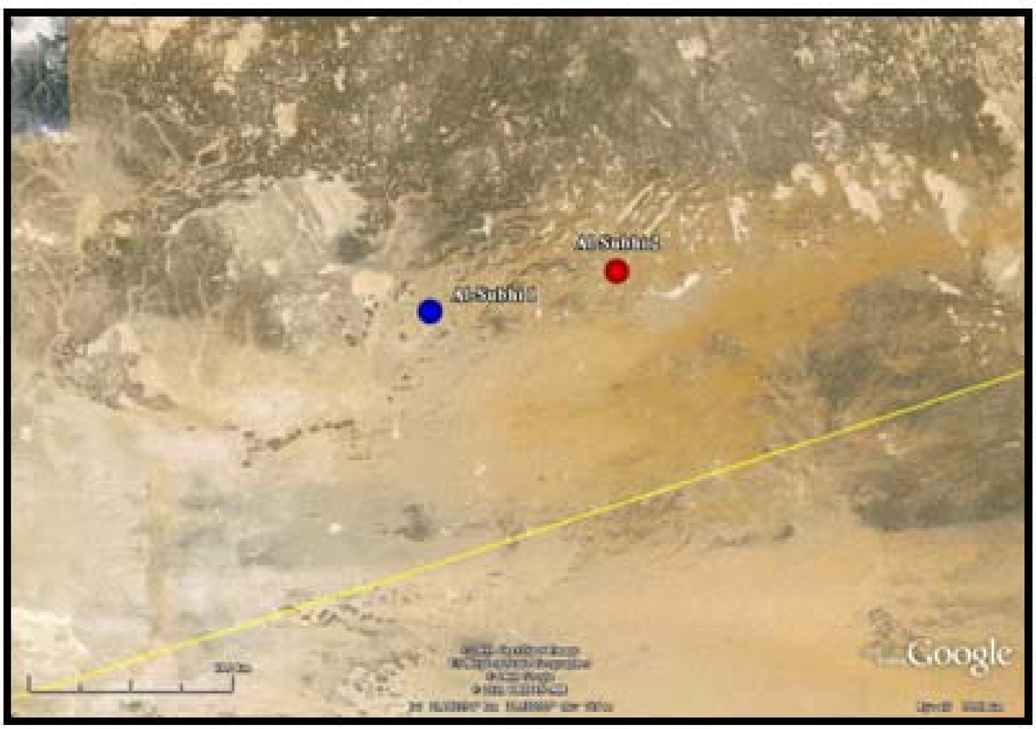


(a)



(b)

Fig. 1: Investigated sites

Table 2: Generalized geological formation and lithological units at the suggested water harvesting sites (Bender, 1974; NRA, 2001)

Location	Geological formation	Lithology
Al-Subhi area:	Alluvium (Al)	gravel, basalt, sand, chert, wadi sediment, limestone
	Alluvium mudflat (Alm)	clay and sand
	Abed Olivine phyric Basalt (AOB)-safawi group	basaltic flood lava (10 m thickness), feeder dike system,
	Wadi Shallaleh Chalk (WSC);	chalk concretion, chalk, sand, limestone
	•Thulaythuwat Chalk (TC)	
	•Dahikiya Sandstone (DHS)	Massive Sandstone (Sst), nummulites,
AlAssra site	Madhala Olivine phyric Basalt formation (MOB):	basalt beds, fresh olivine crystal
	Ufayhim xenolithic basalt formation (UM):	pahoeho flow, iherzolite, dunite, xenoliths
	Aritayn volcanoclastic formation (AT):	bedded, poorly cemented, air-filled tephra.
Wadi Ali (Al-Abed)	Ali doleritic trachytic basalt (AI):	rough, block, massive and rugged in places, irregular shaped basalt boulders (25 thickness)
Al-Guliasi site	Madhala Olivine phyric Basalt formation (MOB):	basalt beds
Ghadeer Al-Naqa site	Soil (S)	loose, poorly sorted clasts of chert, Lst, basalts, wadi sediment
	Fahda vesicular basalt formation (FA)	massive basalts bed, very hard, pipes and clustered vesicular

GEOPHYSICAL FIELD WORK

The site conditions, such as: topography, ground surface complexity as basaltic boulders outcropping and the presence or absence of geophysical noise (e.g. electrical power lines, main road, fence lines etc...), controlled the geophysical application method to be used at each of geophysical test sites.

Electrical field survey: In the Present study, Vertical Electrical resistivity Sounding (VES) method was used with a Schlumberger configuration; it is a four-point arrangement. In this method, the electrical current is injected into the ground by a pair of surface electrodes, the resulting potential field (Voltage) is measured at the surface between a second pair of electrodes, then the subsurface apparent resistivity can be calculated by knowing the spacing and arrangements of the electrodes locations, applied current and measured voltage. An ABEM campus Geopulse resistivity meter was used for field data collection. The calculated apparent resistivity measurements were plotted against half of the current electrode spacing (AB/2) on a log-log scale, a traditional interpretation techniques by curve matching and drawing auxiliary point diagram (Orenella and Mooney, 1966) was applied. Based on this preliminary interpretation, an initial estimation of resistivities and thicknesses of various geo-electrical layers was obtained; these preliminary estimations were later used as a start model for a fast computer-assisted interpretation RESIST written by Vander Velpen and Sporry (1993). The interpreted results were compared with the result of automatic interpretation method (Zohdy and Bisdorf, 1989). The optimum objective of applying geo-electrical methods is to investigate the lateral and vertical distribution of resistivity. The results obtained from the computer

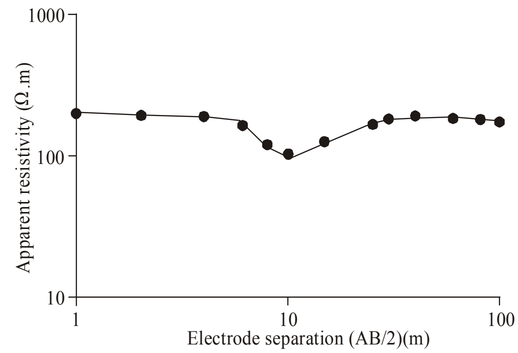
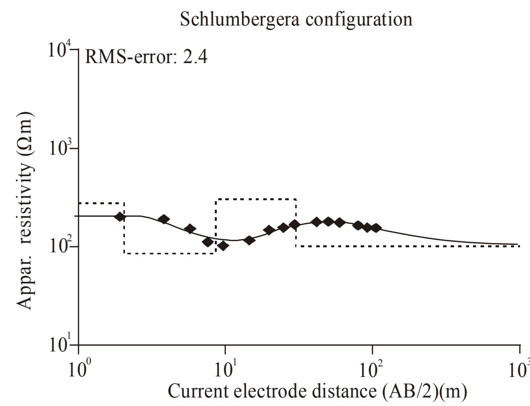


Fig. 2: Field resistivity curve of Al-Subhi-1 site



No	Res	Thick	Depth
1	198.9	1.0	1.0
2	259.0	1.1	2.1
3	80.9	7.2	9.3
4	283.2	21.7	30.0
5	103.8	–.-	--.-

Fig. 3: Multilayer best-fit model of Al-Subhi-1 Site

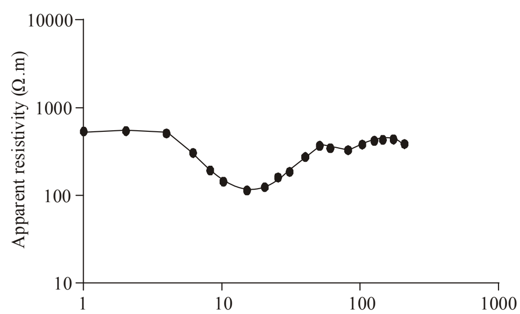


Fig. 4: Al-Ghulaisi-field resistivity curve

Table 3: Results of resistivity soundings

Location	Layer no.	Resistivity (Ohm.m)	Thickness(m)	Suggested interpretation based on the available geological data
Al-Subhi-1	1	199-260	3.1	low-moisture sandy soil, alluvium deposits comprising of gravel, basalts boulders, pebbles, cobbles and a mixture of wadi sediments
	2	81	7.2	high-moisture sandy alluvium deposits and wadi sediments
	3	284	21.7	the bulk resistivity increases and reaches to more than 280 Ω.m reflecting a meaningfully lithological contact at 10 m-depth.
	4	103	unknown	
AlAssra	1	600-900	0-2 m	thin layer (Batayneh *et al*., 2001)
(Batayneh *et al*., 2001)	2	100-400	unknown	dense basalt formation
	3	1000-3200	unknown	rounded, semi globular and oval fracture tuff bodies
Al-Ghuliasi	1	320-960	2.8	low-moisture top soil, boulders of basalts, weathered basalts, wadi sediment and gravel, fractured and jointed basalts
	2	33-78	5.6	high-moisture or saturated layer, saturated wadi sediment and fractured basalts
	3	220-624	8.3	low-moisture, fractured basalts, vesicular and jointed basalts *MOB*
	4	700-1160-1212	42.4	massive, dense, thick bedded of basaltic rocks belongs to *MOB* formation
	5	214	unknown	low resistivity zone, high-moisture or saturated layers with unknown thickness
Ghadeer Al-Naqa	1	5-50	6	top soil, fluvial deposits
VES-1	2	135-275	14	low-moisture zone, intermediate resistive zone,
	3	35-90	48	low resistivity layer, likely saturated wadi sediments
	4	275	28	low-moisture layer, intermediate resistive zone, vesicular basalt that could be attributed to (B5/B6) lava flows
	5	1585	unknown	massive hard and dense basaltic lava rocks
Ghadeer Al-Naqa	1	10-69	4.6	top soil, fluvial deposits
VES-2	2	135-270	8	low-moisture and intermediate resistive zone,
	3	43-70	50	low-resistivity layer, could be saturated wadi sediments
	4	146	32	intermediate resistive zone, vesicular basalt that could be attributed to lava flows
	5	735	unknown	massive hard and dense basaltic lava rocks
Al-Subhi-2	1	30-355	1.1	silt, clay, sand, mud flat, Qaa' deposits
	2	1.7-4.9	7.9	clayey zones, or saturated alluvial
	3	19	3.9	mud flat
	4	65	5.9	clay deposits
	5	184	10	wadi sediments, rock fragments
	6	>1000	unknown	bedrock (basalts)

No	Res	Thick	Depth
1	458.4	0.6	0.6
2	616.8	0.3	0.9
3	957.4	0.4	1.4
4	812.8	0.6	2.0
5	319.9	0.8	2.8
6	78.3	1.2	4.0
7	33.2	2.0	6.1
8	66.3	2.4	8.4
9	219.3	3.2	11.6
10	623.9	5.1	16.7
11	1211.4	9.3	26.0
12	1161.9	13.9	39.9
13	691.5	19.2	59.1
14	214.1	-	-

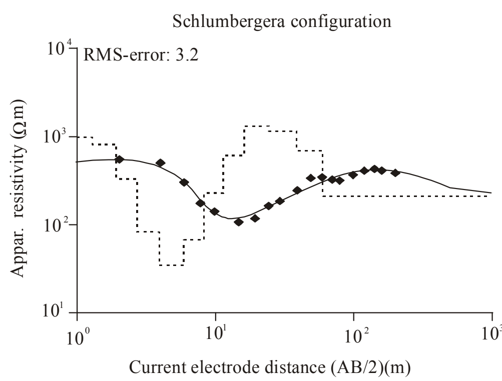


Fig. 5: Multilayer best-fit model of Al-Ghulaisi

modeling are presented in Table 3, while (Fig. 2 to 5) show examples of two VES curves and their best-fit geoelectrical interpretation. The surface geological information (NRA, 2001) and the limited well log-records nearby the geophysical test sites were utilized in the geological interpretation of the geophysical dataset.

VES at Al-Subhi-1 site: The interpreted resistivity model of this site depicts the presence of three main layers (Fig. 2 and 3 and Table 3). The top surface layer is composed of low-moisture sandy soil, alluvium deposits comprising of gravel, basalt boulders and mixture of wadi sediments, with thickness around 3 m and average resistivity of 220 Ω.m. The second 7 m-thickness and of 81 Ω.m-resistivity layer is composed of high-moisture sandy alluvium deposits and wadi sediments. The third layer is characterized by high-resistivity values (280 Ω.m) and 22 m-thickness, reflecting a meaningfully lithological contact at depth 10 m.

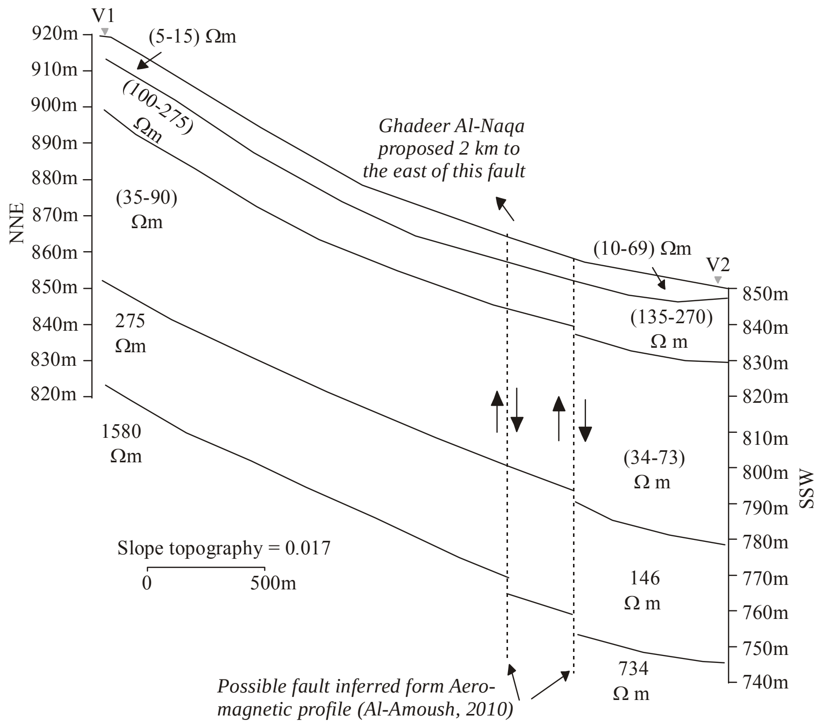


Fig. 6: A geo-electrical cross-section along V1 and V2 at Ghadeer Al-Naqa area

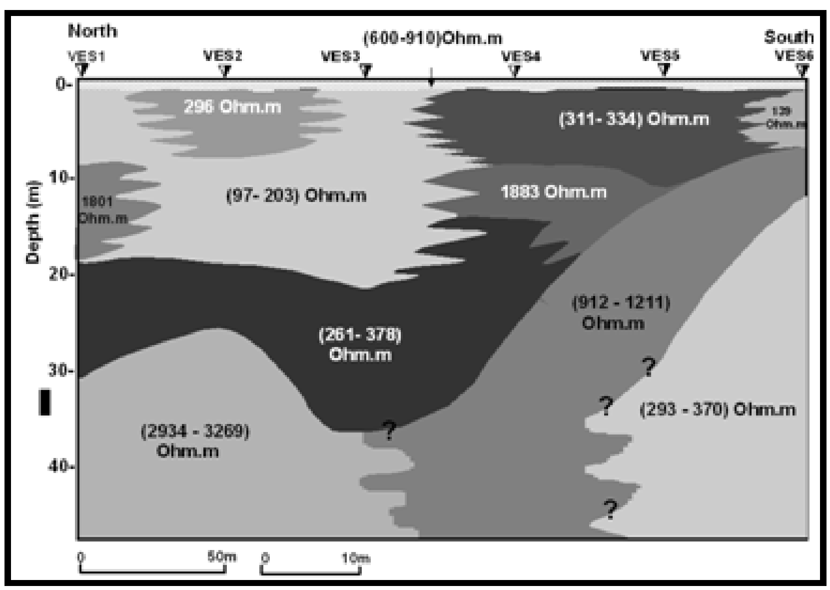


Fig. 7: Interpreted N-S geo-electrical cross section at AlAssra site (modified after Batayneh *et al*., 2001)

VES at Al-Subhi-2 site: The interpreted resistivity model of the site is presented in Table 3. The top surface layer is composed of soft clay, silt, mud flat, Qaa deposits. The obtained results infer the presence of near-surface low-resistivity layer (1.7-4.9 Ω.m). In addition, high-resistivity bedrock (>1000 Ω.m) were found at depth reaching 25 m.

VES at Al-Ghulaisi site: The interpreted resistivity model of this site (Table 3, Fig. 4 and 5) infers the following stratigraphic distribution: an uppermost 2.8 m-thickness and 320-960 Ω.m-resistivity layer composed of low-moisture top-soil, boulders of basalts, weathered basalts, wadi sediment and gravel and fractured and jointed basalts. The second layer is composed of high-moisture or sediment, saturated wadi sediment and fractured basalts, with thickness of 5.5 m and average resistivity of 50 Ω.m. The third layer is composed of low-moisture sediments, fractured basalts, vesicular and jointed basalts, with thickness of 8.5 m and resistivity ranging 220-624 Ω.m. The fourth layer is composed of massive, dense and thick bedded of basaltic rocks belonging to *MOB* formation, its thickness is 42 m and resistivity ranges 700-1212 Ω.m.

VES-1 and VES-2 at Ghadeer Al-Naqa site: The interpreted best-fit resistivity model of this site indicates the presence of four main layers; their geological interpretation is presented in (Table 3) (Al-Amoush, 2010). In this study, a geo-electrical cross-section between VES-1 and VES-2 has been constructed (Fig. 6). A likely faulted area is located just at western of the suggested water harvesting site (Fig. 6) as indicated by (Al-Amoush, 2010). In Addition, low-resistivity layer (35-90 Ω.m) at depth ranging from 13-20 m is depicted in both V1 and V2.

VES at AlAssra site: Batayneh *et al*. (2001) have performed a geophysical investigation including geo-electrical and seismic refraction methods at AlAssra site in order to investigate the subsurface structures and geological formations for proposed dam in Al-Bishriyya (Arityan) area. A summary of their invaluable study is presented in Table 3, while (Fig. 7) shows a modified N-S geo-electrical cross section at AlAssra suggested water harvesting site. The geo-electrical section depicts a near-surface high-resistivity and thin layer (600-910 Ω.m). A relatively lower-resistivity layer (97-400 Ω.m) is identified throughout the section at depths ranging from 4-35 m beneath VES3, which is interpreted as dense basalts formation (Batayneh *et al*., 2001). A very high-resistivity layer (from 900 to >3000 Ω.m) were recorded at depths from 8 m beneath VES6 to 35 m beneath VES3, which were interpreted as rounded, semi globular and oval fracture tuff-bodies (Batayneh *et al*., 2001)

Geo-magnetic field surveys: A Proton precession magnetometer (sensitivity less than 1 nT) instrument (G-820-Geometrics-model) was used for field measurements collection, the total magnetic field data were recorded along profiles at specific and pre-defined equally spaced-points. A base station was chosen close to the surveying profile, in order to record and monitor the time variations in total magnetic field caused by diurnal and magnetic storms as well as for correcting the measured total magnetic field measurements. In this study, non magnetic storms were noticed during the magnetic surveys. In addition, time, GPS-coordinates, elevation and profile azimuths were recorded at each site for further analysis operations. The periodic published International Geomagnetic References Field (IGRF) model maps for the year 2010 were used at each survey site to support in calculate and removing the regional magnetic field for isolating the desired magnetic anomaly for further subsequent modeling.

Table 4: Structural indices and associated symbols

Structural index	1	1.5	2	2.5	3
Symbol	+	X	□	*	^

The interpretation of corrected geo-magnetic measurements were done using automatic interpretation techniques based on Euler deconvolution (Durrheim and Cooper, 1998; Thompson, 1982), a method can assist the interpreter by the portion of the data of interest. The method assumes no particular geological initial-model, despite it lies on the basis of elementary magnetic distributions as the sources of the anomaly (Durrheim and Cooper, 1998). Euler deconvolution (Thompson, 1982) method allows calculating the vertical and horizontal gradient as well as reduced to the magnetic pole field from the original corrected data. The algorithm is making use from the property that the intensity of magnetic anomaly from arrangements of poles or dipoles has a characteristic decay with distance. Structural index, involved into algorithms decay equations, is a value that can be assumed between 0-3 (Durrheim and Cooper, 1998). Table 4 lists the assumed structural indices and their associated symbols.

Geo-magnetic profile in Al-Subhi-1 suggested water harvesting site: In Al-Subhi-1 suggested water harvesting site, a ground micro-magnetic survey was carried out in order to characterize the shallow subsurface structures and to investigate the lateral variations of geo-magnetic field produced by lithological and structural variations. The micro-magnetic profile was 280 m-long, N160º oriented and the measurements spacing were 10 m. The diurnal corrected total magnetic field intensity, vertical gradient; horizontal gradient, Euler's depth-source solutions and geological interpretation along the micro-magnetic profile are shown in Fig. 8. The profile reveals the followings features:

- The causative magnetic bodies producing the anomalies appear at depths ranging from 4-30 m.
- Several negative and positive anomalies named P and N respectively are clearly shown. These anomalies could reflect the lateral lithological and litho-facies variations, faulted formations and/or subsurface basaltic feeder dikes of lava floods of different mineralogy.
- The thickness of the top surface non-magnetic layer is ranging from 4-10 m along the profile, in accordance with the results of geo-electrical investigation (Table 3).

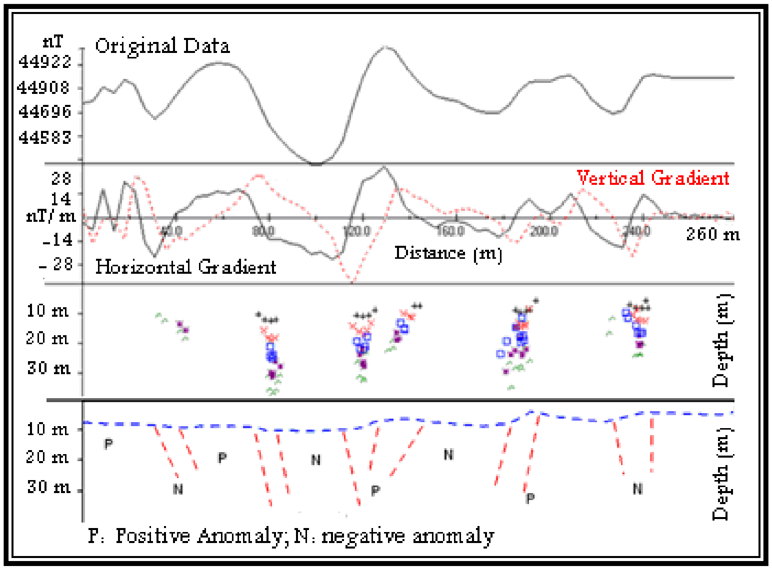


Fig. 8: Euler deconvolution and geological interpretation of micro-magnetic profile at Al-Subhi-1

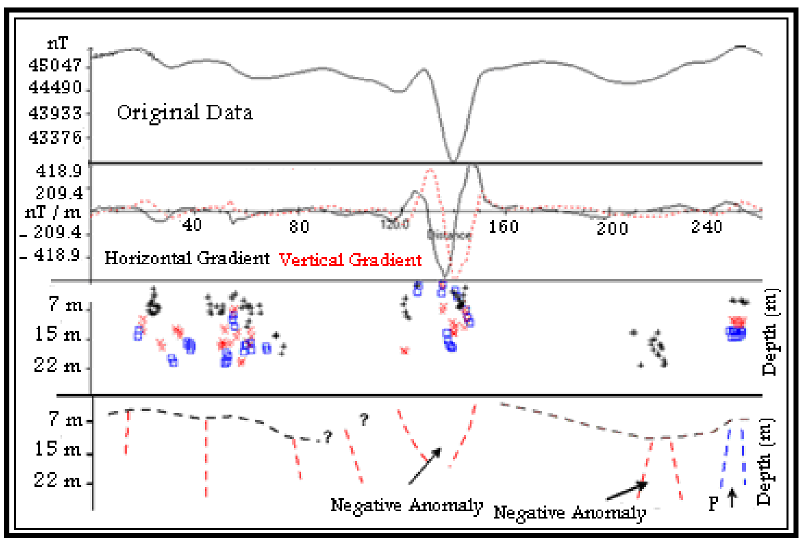


Fig. 9: Euler deconvolution and geological interpretation of micromagnetic profile-1 (E-W) at Al Ghulaisi

Geo-magnetic profiles in Al-Ghulaisi: Two orthogonal ground micro-magnetic profiles were carried out in Al-Ghulaisi. The E-W micro-magnetic profile was 280 m-length and measurements spacing was 10 m, whereas, the second N-S orthogonal profile was 80 m-length and 5 m-spacing.

Micro-magnetic profile-1: The time-corrected total magnetic field along this profile, the horizontal gradient, vertical gradient curves, the modeled (Euler solutions) magnetic data and their geological interpretation are presented in Fig. 9, with the following findings:

- The profile infers the presence of several subsurface faults producing positive and negative anomalies.
- The depth of magnetic causative bodies is ranging from ground surface, at the center of the profile (X = 130-150 m), to a depth of 20 m.
- The main magnetic anomaly is depicted at X = 140 m, where the total magnetic field is declining by magnitude of 150 nT within a few meters. The magnetic field recording at this point (X = 140 m) was repeated many times to assure that the reading was reflecting the real subsurface geology avoiding noise-effect (it was one of the base stations used in

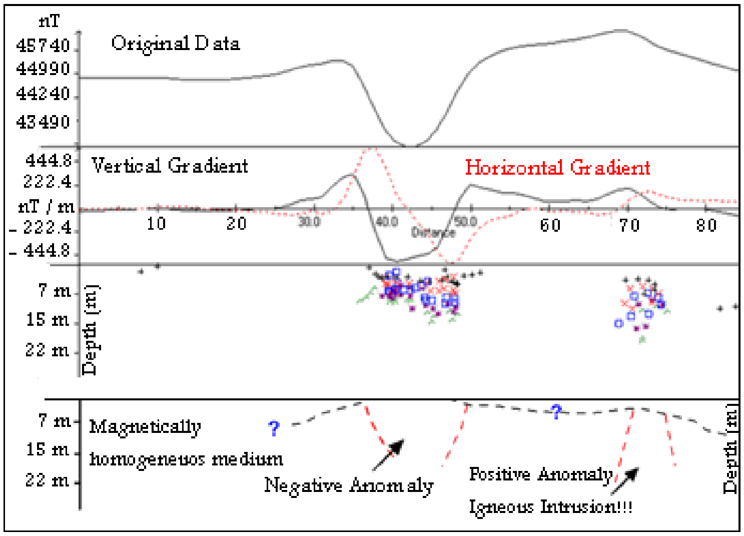


Fig. 10: Euler deconvolution and geological interpretation of micromagnetic profile-2 (N-S) at Al-Ghulaisi

the survey). Additionally, in order to further characterize this negative anomaly, another orthogonal micro-magnetic profile, centered at X = 140 m with a 5 m-spacing, was carried out.

- The thickness of the non-magnetic top surface layer (with the exception of the main negative anomaly) is ranging from 4 m to about 13 m at X = 220 m.

Micro-magnetic profile-2 in Al-Ghulaisi: The time-corrected total magnetic field along this profile, the horizontal gradient, vertical gradient curves, the modeled (Euler solutions) magnetic data and their geological interpretation are presented in Fig. 10, clearly depicting two main magnetic anomalies:

- A negative magnetic anomaly at X = 40-50 m, related to the negative anomaly identified at X = 140 m in profile-1. This anomaly could be interpreted as a subsurface igneous intrusion of different mineralogical composition with the host rocks, a subsurface basaltic cave and/or a fault zone.
- A positive magnetic anomaly is depicted at X = 70-75 m, which could be attributed to a shallow subsurface igneous intrusion.
- From X = 0 to X = 25 m, the profile shows a quite magnetic homogeneous materials.

SOIL INVESTIGATION

Soil texture could be considered a key aspect when selecting a site for a water harvesting scheme, especially if the purpose of this scheme is preserving the water for human, livestock and agricultural purposes (Al-Adamat, 2008). The highest infiltration capacities are observed in sandy soils while heavy clay or loamy soils have considerable smaller infiltration capacities (Noman and Tahir, 2003). According to Critchley *et al.* (1991), serious limitations for the application of water harvesting are soils with a sandy texture.

In order to investigate the soil suitability for water harvesting in the selected sites, 9 soil samples were collected from each site. The samples were collected from the bottom (3 samples) and the left and right banks of the wadi (3 samples from each side). The starting point of sampling was the suggested dam site and then moving towards the inlet of the dam. The distance between each two samples was 50 m. The soil samples were collected from the top 25 cm (approximately 1 kg of soil). Each sample was subjected to Particle Size Distribution analysis (PSD) to determine the percentages of sand, silt and clay. The soil texture for each sample was determined using the USDA soil texture calculator. Table 5 provides a description for the outcomes of textural analysis. The high sand percentages determined for the collected soil samples correspond to the samples that were collected from the bottom of the wadi (fine sediment). According to Al-Adamat *et al.* (2010), soils with clay percentage of more than 18% are considered suitable for establishing water harvesting schemes. So, based on the results described in Table 5, Al-Subhi-1 site is not suitable for establishing water harvesting dam, since the average clay for the site is 11%, while the average sand is 82%. The other five sites were considered suitable for establishing water harvesting dams. The average clay in these sites exceeds 26%, while the average sand ranges 5-46%.

Table 5: Soil analysis results

Site	Sand % min	Sand % max	Silt % min	Silt % max	Clay % min	Clay % max	Average soil texture
Al-Subhi-1	70	94	2	12	6	20	loamy sand
Average %	82		7		11		
Al-Subhi-2	24	60	8	34	32	42	clay loam
Average %	43		20		37		
Ghadir Al-Naqa	37	50	22	41	22	30	clay loam
Average %	44		29		27		
Al-Ghulaisi	24	64	16	42	20	42	clay loam
Average %	45		28		27		
Al-Abed	26	48	30	50	20	32	clay loam
Average %	35		38		27		
AlAssra	32	60	4	44	10	38	clay loam
Average %	39		29		32		

CONCLUSION

In this study, a geophysical survey including Vertical Electrical resistivity Sounding (VES) ground geo-magnetic methods, soil sampling and soil textural analysis were performed at suggested water harvesting sites in the Northern Jordanian Badia to investigate and characterize the shallow subsurface stratigraphic sequences and structures. The interpretation of Geo-electrical soundings gave preliminary indications of the nature of the lithological layers and their thicknesses and average depths.

The micro-magnetic surveys has provided good results regarding the shallow subsurface lateral structural variations at the surveyed sites. The geo-magnetic results at Al-Subhi-1 and Al-Ghulaisi sites infer the presence of several positive and negative magnetic anomalies which reflect the lateral subsurface variations produced by faults and lithological variations. The thickness of the top surface non-magnetic layer was found to be ranging 4-10 m in Al-Subhi-1 site and 4-13 m in Al-Ghulaisi site. The near subsurface faults could enhance the water leakage which reduces the suitability of these sites as water harvesting sites.

On the basis of the obtained results, although of the well-known ambiguity associated with geoelectrical resistivity interpretation, as several of geological layering can produce the same geophysical anomalies, it can be concluded that the Geo-electrical (VES) and ground geo-magnetic techniques can provide an inexpensive, fast methods for characterizing the shallow subsurface lithology and structures for water harvesting site investigation. These preliminary results show that five sites could be suitable for establishing water harvesting dams, while one site (Al-Subhi 1) is not suitable for such purpose because the top surface layer is composed of sediments of high infiltration capacity (e.g. dry sandy soil, alluvium deposits comprising of gravel, basalt boulders and mixture of wadi sediments, with thickness around 3 m. The second layer 7 m-thickness is composed of wet sandy alluvium deposits and wadi sediments).

Textural analysis also supported that Al-Subhi-1 was not suitable for establishing water harvesting dam, since the average clay for the top-soil site 11% which is relatively low compared with the other sites, while the average sand is 82%. The other five sites were found to be suitable for establishing water harvesting dams. The average clay in the top-soil of these sites is more than 26%, while the average sand is less than 46%.

In conclusion, it is worth to say that these results are considered a preliminary findings, However, further geophysical investigations including the use of Ground Penetrating Radar (GPR) and 2D-Electrical Resistivity Tomography (ERT) are recommended to conclusively decide if these sites are suitable or not for water harvesting.

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