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The Use of GIS Techniques and Geophysical Investigation for Flood Management at Wadi Al-Mafraq Catchment Area

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Abstract

The rapid expansion of urban areas over the past two decades within Mafraq City has affected the surface hydrology runoff. Developments in Mafraq City have changed the land coverage from vegetation to impervious surface (Asphalt and Buildings) which covers most of the urban areas within Mafraq City. This reduced the ability of the land to absorb rainfall and force the excess rainfall-runoff to flow faster over the surface. As a result, the West and central regions of Mafraq City recently experienced floods that have affected hundreds of people. In order to control flood and minimize its impacts on local people, it is necessary to manage such floods. The present study aims at identifying the potential sites for water harvesting dam within the Wadi Al-Mafraq watershed to control the flood that pass through the city using GIS techniques. In order to select the potential site for the water-harvesting dam, five physical criteria that affect the water harvesting were identified based on a literature review. These criteria are rainfall, soil texture, slope, material of vadoze zone and drainage density. Based on the use of the Weighted Linear Combination (WLC) method, a water harvesting potential map was generated. The outcome of the GIS analysis was validated by fieldwork investigations carried out using Time Domain Electromagnetic Geophysical method (TDEM). The TDEM results show that (10 - 25) m of silty clay, soil and alluvium deposits are dominated the proposed site as the topmost layer. Moreover, three to four distinctive subsurface geo-electrical layers were identified in terms of their resistivity, thicknesses and structures. The present study proves the importance of the integration of different techniques GIS and TDEM in water harvesting and flood management studies.

Keywords: Flood management, TDEM, Wadi Al-Mafraq, GIS, Water harvesting.

1. Introduction

The rapid expansion of urban areas over the past two decades within Mafraq City has impacted the surface hydrology runoff. Developments in Mafraq City have changed the land coverage from vegetation to impervious surface. Impervious concrete and asphalt surfaces cover most of the urban areas within Mafraq City, which reduces the ability of the land to absorb rainfall and force the excess rainfall-runoff to flow faster over the surface.

Accumulation of water in certain areas can be the main causes of localized flooding problems. The west and central regions of Mafraq City have recently experienced floods that have affected hundreds of people. Although no inhabitants appear to have been physically harmed, many homes and roads were affected. According to reports published in national newspaper, Wadi Al-Hussein passing through Mafraq City attained high floodwater levels that constitute a significant danger in particular, where the main road crossing the Wadi. The road was closed as sections were swamped by up to a three meter of water, and flash floods overwhelmed drainage system, forcing the closure of most road tunnels and grid locking traffic (Addustour newspaper, 10/10/2011) (Figures 1a and b). Most importantly, this disaster will continue with time and the Wadi is widening and forming a dangerous problem on the surrounding houses in center of the city (Figure 1a).

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Figure 1. Flashflood in Mafraq City (a. Addustour newspaper, 10/10/2011 , b. 2016)

In order to counter flood effects, it is very crucial to operate the surface water system for flood control efficiently to minimize the impacts of flood during real-time flood events (Jha et al., 2012). Many flood mitigation structures in the city projects have been implemented in a phased program to rehabilitate and upgrade the existing drainage infrastructure (Charlesworth, 2010).

The early phases were operated on a traditional approach that involved channel improvement works to speed up the flow of the flood wave through the city and the construction of storage facilities upstream to regulate the magnitude of floodwaters flowing into the city (Zevenbergen et al., 2010). There is, however, minimal impacts of such solutions; this is because such flooding still causes a threat to the residential and commercial buildings or other public and private infrastructures (Zevenbergen et al., 2010). A completely new approach for flood control is deemed necessary for the Mafraq City. As a result, a comprehensive flood mitigation system. This system involves a set of structural flood control measures to divert the flood runoff from the catchment through a bypass channel before it is being directed back to the Mafraq City centre downstream and/or construction storage ponds and dams upstream of the city to detain floodwater and attenuate the flood flow into the city. Local planners and decision makers are in dire need for accurate information on the spatial distribution, magnitude and depth of flooding, and on the land use affected. The integration of GIS, remote sensing and Digital Elevation Models (DEMS) with multi criteria decision support system is an active area of research. In recent years, Geographic Information Systems (GIS) and Multi Criteria Decision Analysis (MCDA) have been widely used for water harvesting site selection studies. Several researchers have used GIS and MCDA for water harvesting studies (e.g., Al-Shabeeb, 2015; Al-Shabeeb, 2016; Srivastava, 2001; Gupta et al., 1997; Al-Amoush et al., 2016; El-Awar et al., 2000; Baban and Wan-Yusof, 2003; Shatnawi, 2006; Al-Adamat, 2008; Al-Adamat et al., 2010 and Al-Adamat et al., 2012).

Those researchers used GIS in selecting the best sites for water harvesting projects at various parts of the world. In their search to find the best sites, they applied the Weighted Linear Combination (WLC) within GIS on various thematic layers including geology, land use/land cover, soil types, slope, rainfall and drainage density. WLC is a method of MCDA that is implemented within GIS environment, which defines weights for criteria selected.

In the present study, five physical criteria were used, including the rainfall, the slope, the drainage density, materials of vadose zone and soil texture to select an optimum site for a dam in Wadi Al-Mafraq catchment area to control the flood that passes through Mafraq City. WLC was used for determining the best sites for water harvesting dam in the present study. The selected sites were then validated using Time Domain Electromagnetic Geophysical method in order to investigate the subsurface layering.

2. Study Area

The study area is located in the Northern part of Jordan to the West of Mafraq City (Figures 2 and 3). Figure 3 shows the Wadis that enter Mafraq City from the West and cause the flooding problem. It shows also the corresponding watershed for each Wadi. In the present study, the catchment area of Wadi Al-Mafraq has been thoroughly investigated to establish a flood control system because Wadi Al-Mafraq is the major contributor to the flooding problem within the city. The study area is inhabited by more than 200.000 people (DOS, 2015). The soil clay percentages in the study area is 29% and the soil texture is silty loam (Al-Adamat et al., 2007). The study area topography is predominated with regions of high elevation (918m) in the west and north west and low elevation (675 m) in the eastern parts of the study area (Figure 4). The annual rainfall ranges between 150 mm in the eastern parts to 250 mm in the western parts of the study area (Al-Adamat et al., 2007) (Figure 5). Surface water flows towards Mafraq City from the west and north west (Figure 3).

The study area is situated in an area classified as an arid to semi-arid climate zone with hot summer and cold winter with average temperatures 38°C (Summer) and 14°C (Winter) (Department of Meteorology DOM, 2015). The mean annual rainfall is estimated to be 161 mm and is fairly evenly distributed throughout the winter season (Department of Meteorology DOM, 2015).

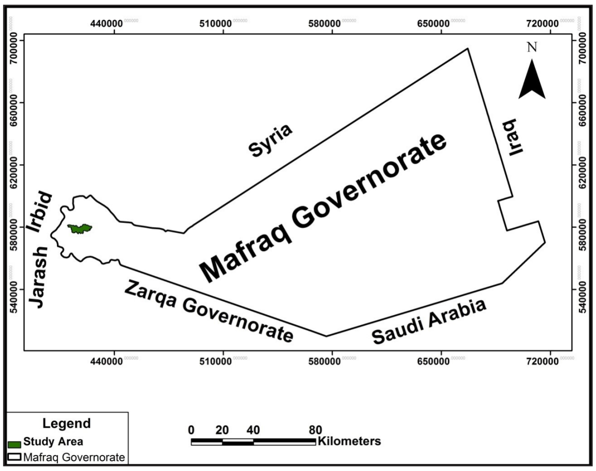


Figure 2. Location map of the study area

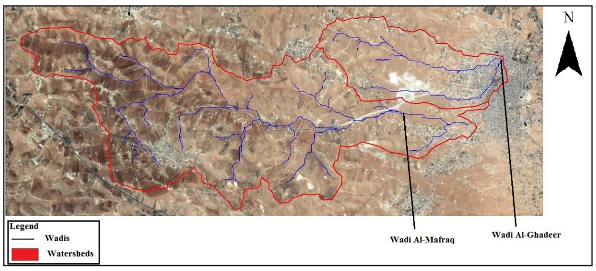


Figure 3. Major Wadis and their watersheds

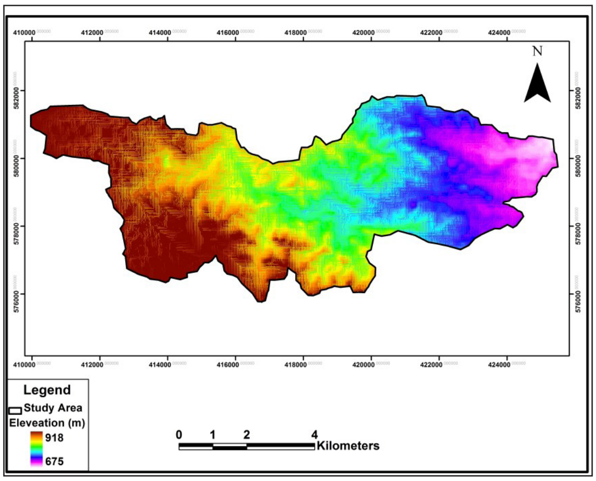


Figure 4. Elevations within the study area (Based on ASTER DEM)

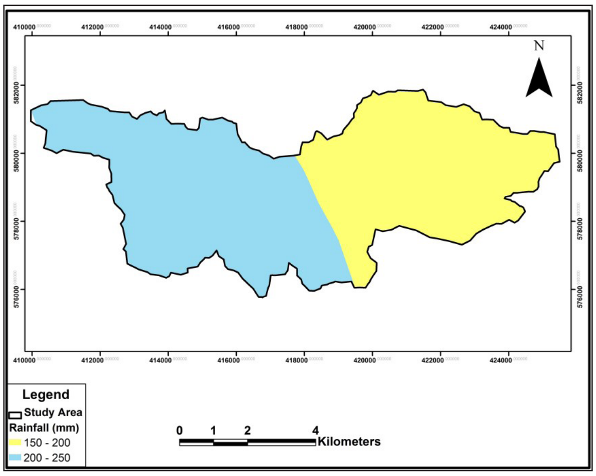


Figure 5. Average annual rainfall within the study area (Modified from Al-Adamat et. al., 2007)

3. Methodology

The methodology adopted for determining the suitable water harvesting sites in the selected areas of the Wadi-Al-Mafraq is presented in Figure 6.

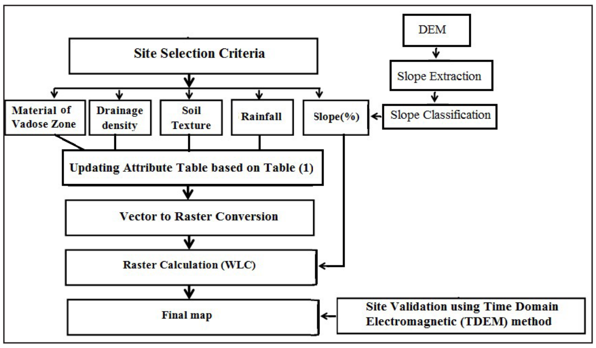


Figure 6. Flowchart of the methodology adopted in this study

Table 1 lists the rates of each parameter and its associated weight score. This table lists only the ratings appropriate for the study area. The attribute table of the rainfall layer (Figure 5) was updated according to Table 1 and then converted to raster format (Figure 7). Based on Figure 6, the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) DEM (spatial resolution of 30 m) (Figure 4) has been used to derive the slopes for the study area and classify them according to Table 1 (Figure 8). It appears, from this table, that the material of vadose zone and soil texture have only one value each to represent the weight by ratings. The entire study area of the same vadose zone material (Limestone). Also, the entire study area of the same soil texture (silt loam). The material of vadose zone has the value of 6 and the soil texture has the value of 2. The ASTER DEM has been also used to derive the drainage network for the study area through the use of Flow Direction and Flow Accumulation calculation techniques within ESRI ArcGIS® (Figure 3). The resulted GIS layer was subjected to density calculation and classification based on Table 1 and the result is shown in Figure 9.

Table 1. The used weights ratings in this study (after Al –Shabeeb, 2016)

Criteria	Condition	Weight (W)	Rating (R)	W×R
Rainfall (mm)	100-200	5	2	10
	200-300		3	15
Slope (%)	> 8%	4	1	4
	4-8%		2	8
	2-4%		3	12
	0-2%		4	16
Material of Vadose Zone	Limestone	3	2	6
Drainage density (km/ km^2)	> 2.55	2	1	2
	1.5 - 2.25		2	4
	0.75 - 1.5		3	6
	0 - 0.75		4	8
Soil Texture	Silt Loam	1	2	2

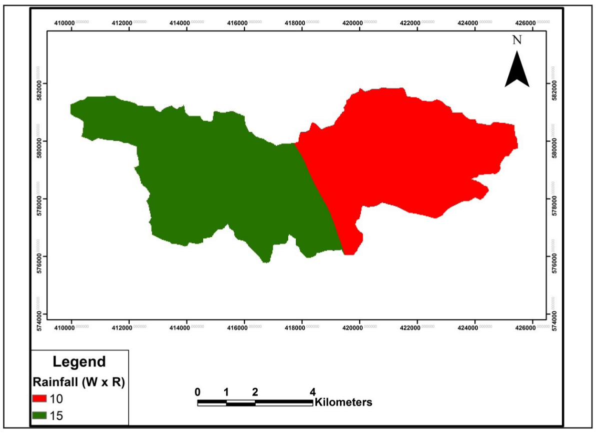


Figure 7. Rainfall (Weight × Ratings)for the study area

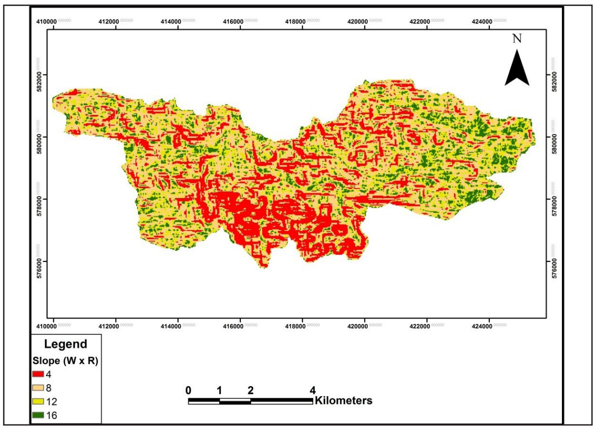


Figure 8. Slope (Weight × Ratings) for the study area

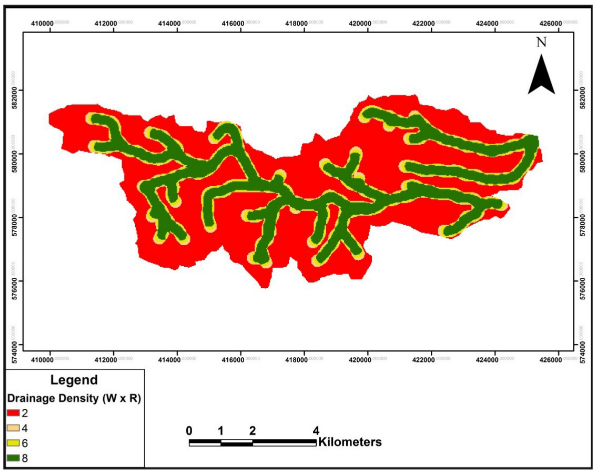


Figure 9. Drainage Density (Weight × Ratings) for the study area

4. Results and Discussion

The GIS layers (Figures 7, 8 and 9) were combined using the raster calculation techniques within ESRI ArcGIS® together with a fixed number of 8 that represents the material of vadose zone and soil texture. Table 2 describes the combination of the GIS layers. The numbers listed in this table represent the cells values of each layer. Figure 10 shows the water harvesting potential within the study area. The map has been classified into four potential classes (Low, Moderate, High and Very High). It is clearly appear from this figure that the most western part of the study area is characterized by a high and very high suitability regions for water harvesting, particularly along the major course of the Wadi and within the Wadi bed.

Table 2. The conducted arithmetic operation for the site selection of water harvesting dam

Rainfall (W×R)	+	Slope (W×R)	+	Material of Vadose Zone (W×R)	+	Drainage density (W×R)	+	Soil Texture (W×R)
10		4		6		2		2
15		8				4		
		12				8		
		16				12		

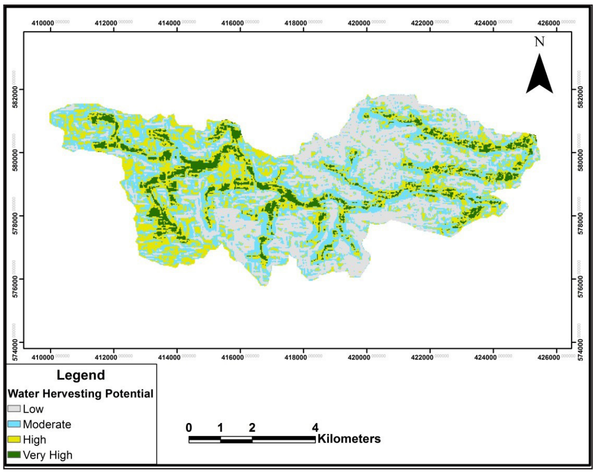


Figure 10. Water Harvesting Potential map

5. Validating the Selected Site Using Time-Domain Electromagnetic Geophysical Method (TDEM)

TDEM method has been widely used for hydro-geological studies (e.g., Danielsen et al., 2003; Goldman et al., 1994; Al-Amoush et al., 2015; Al-Amoush et al., 2016). It was used for environmental applications (e.g., Hoekstra and Blohm, 1990; Mauldin-Mayerle et al., 1998). TDEM was combined with DC electrical resistivity method to investigate the groundwater contamination (e.g., Buselli et al., 1990), for geological mapping (e.g., Jorgensen et al., 2005). For hydro-geophysical and mapping larger structural formation investigations (e.g., Christensen and Sorensen et al., 1995). The theoretical background of TDEM is described in many books (e.g., Reynolds, 2011; Sharma, 1997; Telford et al., 1990; Kirsch, 2006; Keary et al., 2002) as well as in several published articles.

The principle of TDEM is based on generated a primary field which is not continuous but that consists of a series of pulses separated by periods when it is inactive (Keary et al., 2002). During the period of current-on, a static magnetic field is established in the earth (Sharma, 1997; Keary et al., 2002). The eddy currents induced in a subsurface conductor tend to diffuse inward outwards its center when the inducing field is removed and gradually dissipate by resistive heat loss (Keary et al., 2002). This causes a decaying of the magnetic field at the earth surface (Sharma, 1997). The secondary magnetic field can be measured easily. Within highly conductive bodies, the decay of eddy currents (secondary magnetic fields) is significantly slower than that in poor conductors. Measurements of the rate of decay of the secondary magnetic field thus provides a means of detecting subsurface conductive bodies and estimating their conductivities (Sharma, 1997)

In the present study, Time-Domain Electromagnetic (TDEM) method was carried out at specified locations in Wadi Al-Mafraq catchment area as determined by Geographical Information System (GIS) modeling tools based on a pre-defined criteria (include soil texture, slope, material of vadose zone, rainfall and drainage density). The objective of TDEM survey is to investigate the shallow subsurface layering›s (stratigraphy) and structures and to build a 2D - hydro-geophysical models along and across the Wadi course to investigate its suitability for water harvesting dam.

5.1. Field Survey and Geometry

In the present study, eight TDEM sounding points were carried out at the proposed location for water harvesting structure construction (Figure 11). A square transmitter loop (dipole Tx-Rx) configuration with dimension (50m * 50m) was used for data acquisition. The estimated depth penetration was (~130m). The measurements were acquired using a typical TEM-FAST 48HPC system comprising a transmitter (Tx), a receiver (Rx) and unit control managed by HP-IPAQ Pocket system. The measurements were made by transmitting a direct current up to 4 Ampere using 12V batteries with 48 active time gate. A stacking time was set to 7 minutes with 50Hz filter to eliminate aliasing effects. Data processing and modeling was performed using attached software called TEM-RESEARCHER to obtain 1-D models and to construct a 2-D geo-electromagnetic models over the study area. Figure 12 shows the 1-D modeling soundings for the 8-TDEM carried out in the proposed site.

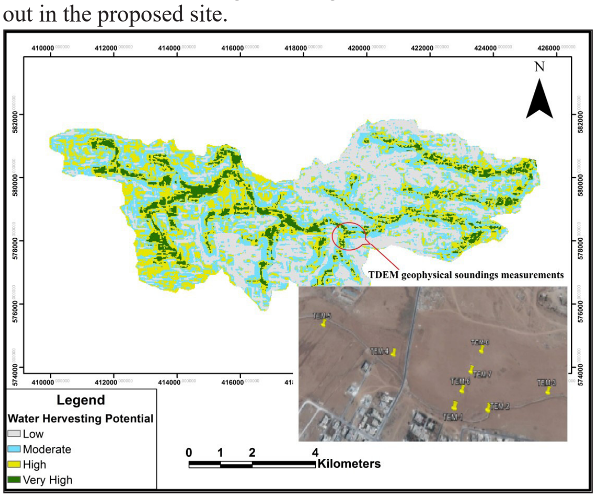


Figure 11. Water Harvesting Potential map and enclosed Google earth map shows the locations of TDEM geophysical soundings measurements

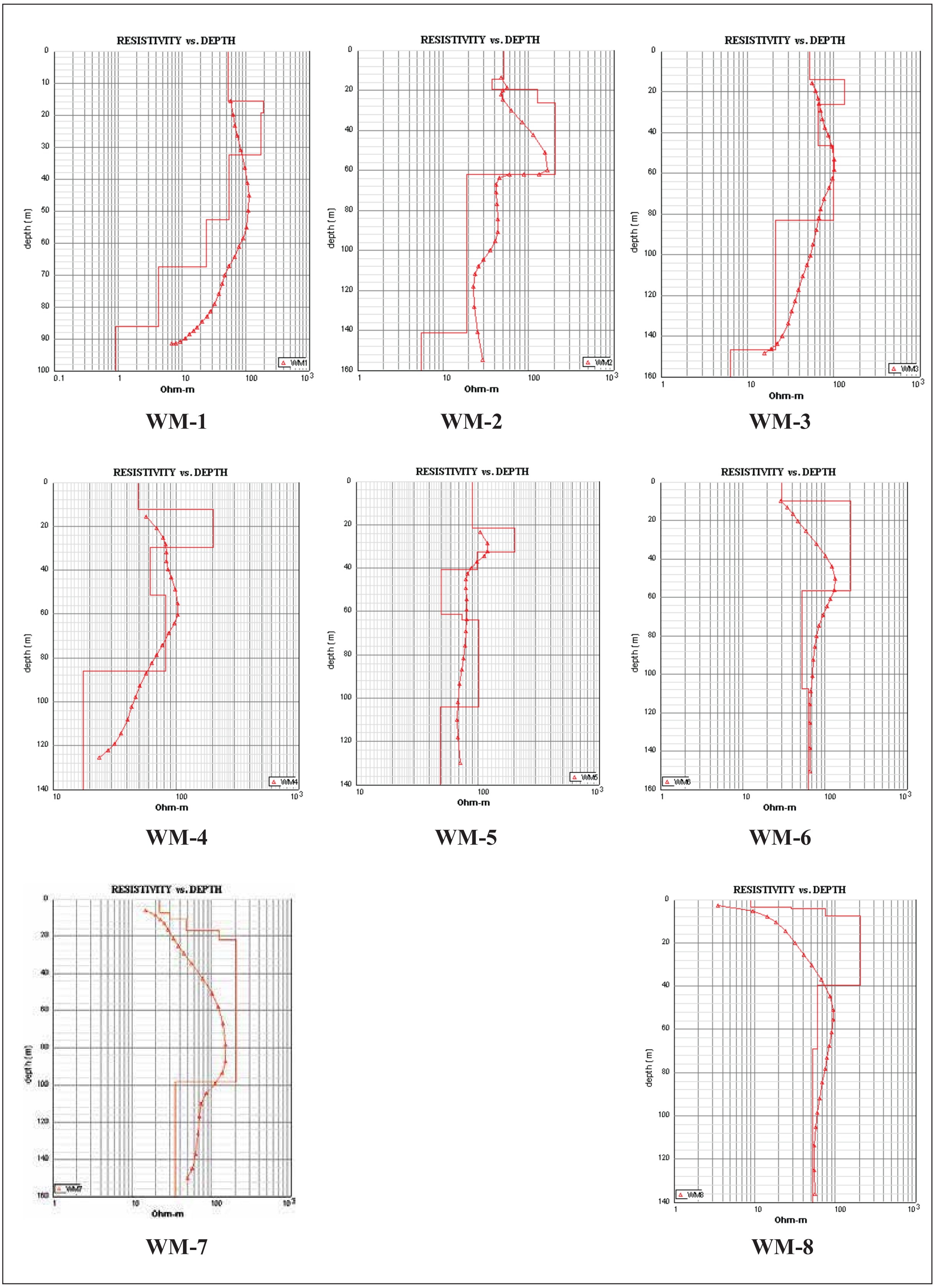
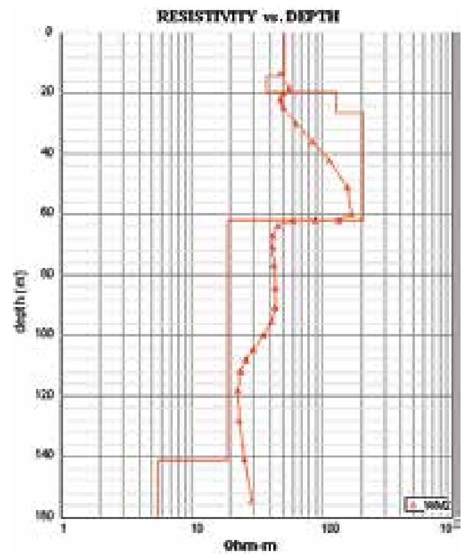
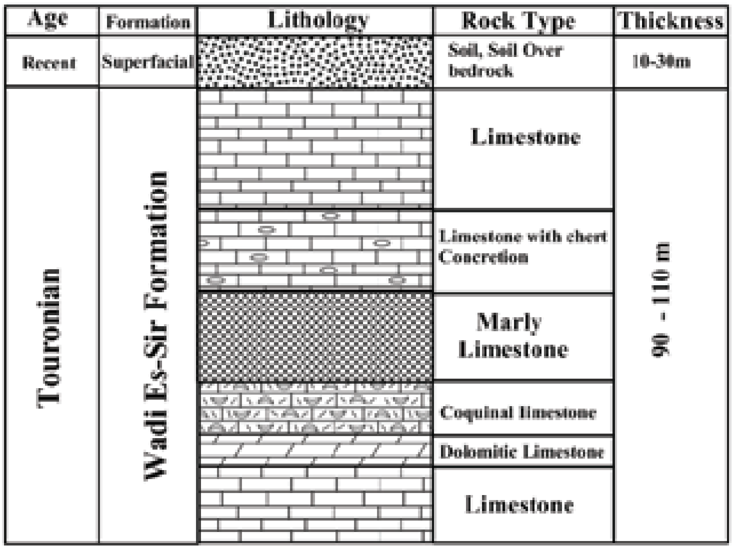


Figure 12. 1- D TDEM modeling soundings at proposed site dam within Wadi Al-Mafarq catchment area

5. 2. Geophysical Data Interpretation

The study area was classified as a dry zone and there was no close boreholes to the proposed dam site investigation. Therefore, the Generalized geological Vertical Section (GVS) and surface geological map as well as the available geological cross sections for the study area were used for interpreting and calibrating the various TDEM soundings and models (Table 3). The TDEM soundings were used to build 2-D geo-electromagnetic resistivity cross-sections in order to investigate the subsurface stratigraphy and structures.

Table 3. a) TDEM measurements and modeling results of sounding TDEM-2 b) Generalized geological Vertical Section(GVS) (Columnar section, Map sheet 3254IV, Geological map of Al-Mafraq) of the study area (Modified after Al-Smadi, 1997)

a)TDEM-2	b) Generalized geological Vertical Section (GVS)
	

5.2.1. WNW-ESE 2-D Geo-Electromagnetic Cross-Section

Figure 13 shows an E-W 2-D geo-electromagnetic cross-section extending along the course of the Wadi. This model links the soundings TDEM-5, TDEM-4, TDEM-2, TDEM-6 and TDEM-3. The inverted model was correlated with the generalized geological vertical section (GVS) of the study area. Four distinctive subsurface units can be recognized in this model. The upper most unit has a low resistivity layer (20-40) Ohm.m, it has thickness in the range of 10 to 20m over the section; this unit correlates with the predominantly impermeable silty clay - soil and alluvium sediments. The second subsurface unit is a resistive layer (180 - 200) Ohm.m. Its thickness is 20m in the western part and 40m in the most eastern part of the model. It can be correlated with the massive-fractured limestone of Wadi Es-Sir formation (WSL). The third subsurface unit has an intermediate to high resistivity (100 - 140) Ohm.m. It is correlated with limestone and marly limestone of WSL. The fourth subsurface unit has low resistivity values (30-70) Ohm.m, extending to a depth down to 140m and could indicate to saturated zone of limestone or marly-limestone of WSL. The geo-electromagnetic model exhibits lateral variations in resistivity and unit thicknesses, which indicates a change in stratigraphical facies along the course of the Wadi. Moreover, significant faults and fractures have been identified between TDEM-4 and TDEM-6, and between TDEM-6 and TDEM-2 (Figure 13).

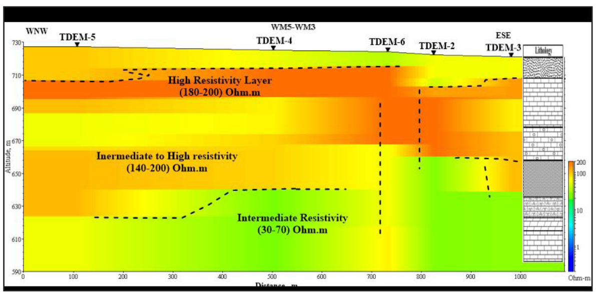


Figure 13. WNW- ESE 2-D Geo-electromagnetic section along Wadi Al-Mafraq based on models of TDEM Soundings (TDEM-5, TDEM-4, TDEM-6, TDEM-2 and TDEM-3). Lithology is interpreted based on a correlation with Generalized geological Vertical Section (GVS) of the study area (see Figure 11 for location)

5.2.2. N-S 2-D Geo-Electromagnetic Cross-Section

Figure 14 shows a N-S 2D geo-electromagnetic cross-section extending a cross the Wadi. The section links the soundings TDEM-1, TDEM-6, TDEM-7 and TDEM-8. The inverted model is correlated with the generalized vertical section (GVS) of the study area. In this model, three distinctive subsurface units can be recognized; the first subsurface is a low resistivity subsurface unit (20-40) Ohm.m.; it has a thickness in the range 15-25m. This unit can be correlated with the predominantly impermeable silty-clay, soil and soil over bedrock. The second subsurface unit is a high resistivity (150 - >200) Ohm.m unit. Its thickness varies along the model (40 - 60)m. It can be interpreted as a paleo-channel deposits composing of blocks of limestone, gravel and wadi sediments especially under TDEM-7. Another explanation for this unit is a layer consisting of massive-fractured limestone corresponding to WSL formation bounded by vertical faults and joints. The third subsurface unit has an intermediate resistivity (40-90) Ohm.m with 70m -100m in thickness. It correlates with limestone to marly limestone of Wadi Es-Sir limestone (WSL).

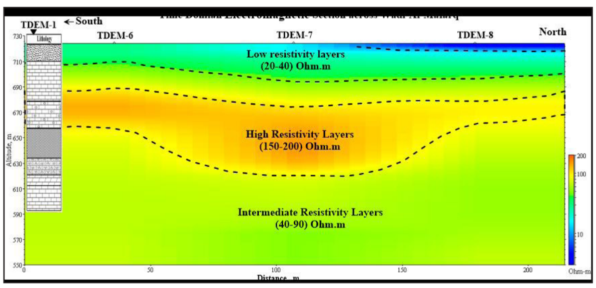


Figure 14. N-S 2-D Geo-electromagnetic cross section across Wadi Al-Mafraq based on models of TDEM Soundings (TDEM-1, TDEM-6, TDEM-7 and TDEM-8). Lithology is interpreted based on a correlation with generalized vertical section (GVS) of the study area (see Figure 11 for location)

6. Conclusions:

The main aim of this study is to map the potential sites for water harvesting suitability and to select an optimum site for a dam in Wadi Al-Mafraq catchment area to control the flood that pass through Mafraq City during winter times. In order to achieve the objectives of the study, different thematic maps (e.g., rainfall, soil texture, drainage density, slope derived DEM and vadose zone materials) were gathered from different resources and organized, incorporated within Geographical Information System tools (GIS). The final harvesting suitability model map for the study area was produced based on the use of Weighted Linear Combination (WLC) techniques, where each GIS layer has its ratings and weights. Water harvesting potential to control flood within the Mafraq City caused by Wadi Al-Mafraq runoff was classified into four classes (Low, Moderate, High and Very high). A significance site located within the high water harvesting potential to the West of Mafraq City was selected to perform a Time Domain Electromagnetic geophysical method as a validation to investigate the subsurface geological layering. The TDEM results show that three distinctive subsurface geo-electrical layers were identified in the proposed site. The topmost layer, composed of (10 - 25) m, is interpreted as a silty clay, soil and alluvium with resistivity of (20-40) Ohm. m. The second subsurface layer, composed of 20m to 60m and resistivity of (150 - >200) Ohm.m, is interpreted as a massive fractured limestone and/or a paleo-channel deposits. The third subsurface layer, with resistivity of (40-140) Ohm.m and depth reaches 140m, is interpreted as a massive fractured limestone of Wadi Es Sir Limestone (WSL).

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