Derived Relations between Geoelectric and Hydraulic Parameters in Bara Basin, Sudan

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Introduction

- Knowledge of the hydraulic parameters of subsurface aquifers is essential to determine the *natural flow of the groundwater*.
- The hydraulic conductivity K and the transmissivity T are aquifer parameters that vary spatially due to geologic heterogeneity.
- Estimation of K and T allows a quantitative prediction of the aquifer hydraulic response to recharge and pump.
- Better K and T estimation obtain from testing pumping wells TPW, but expensive and time consuming.
- Using surface Geoelectrical method to estimate K and T can greatly reduce the number of TPW.

Introduction

- Relationship between aquifer hydraulic and geoelectric parameters is investigated since 1951 by Jones and Budford, that as the grain size increase, the formation factor and the intrinsic permeability also increase.

- Frohlich (1974) constrained this relation for a given porosity range.

- Empirical-semi empirical relations between the aquifer resistivity and its hydraulic parameters have been correlated under different geological conditions by several hydro-geophysicists as Kelly (1977), Kosinski and Kelly (1981), Frohlich and Kelly (1985), Yadav and Abolfazli (1995).

- Sriniwas and Singhal (1981 and 1985) developed analytical relations between the aquifer transmissivity T and Dar-Zarrouk parameters.

Objectives

i.e.

- We need to make these relations more general in nature and thus more applied widely in areas with diverse lithological characteristics.

So,

- Bara basin, in NKS in Central Sudan, in one of the most important provinces concerning the natural resources in Sudan.

- But, still encounter problems such as high GW salinities and lack of detailed GW assessment.

In the present study,

- A general functional relation is derived between surface resistivity soundings and the hydraulic parameters of the western part of Bara basin.

The Study Area

Physiography:

The ground surface slopes gently E and NE towards the White Nile as the perennial watercourse bounding the study area.

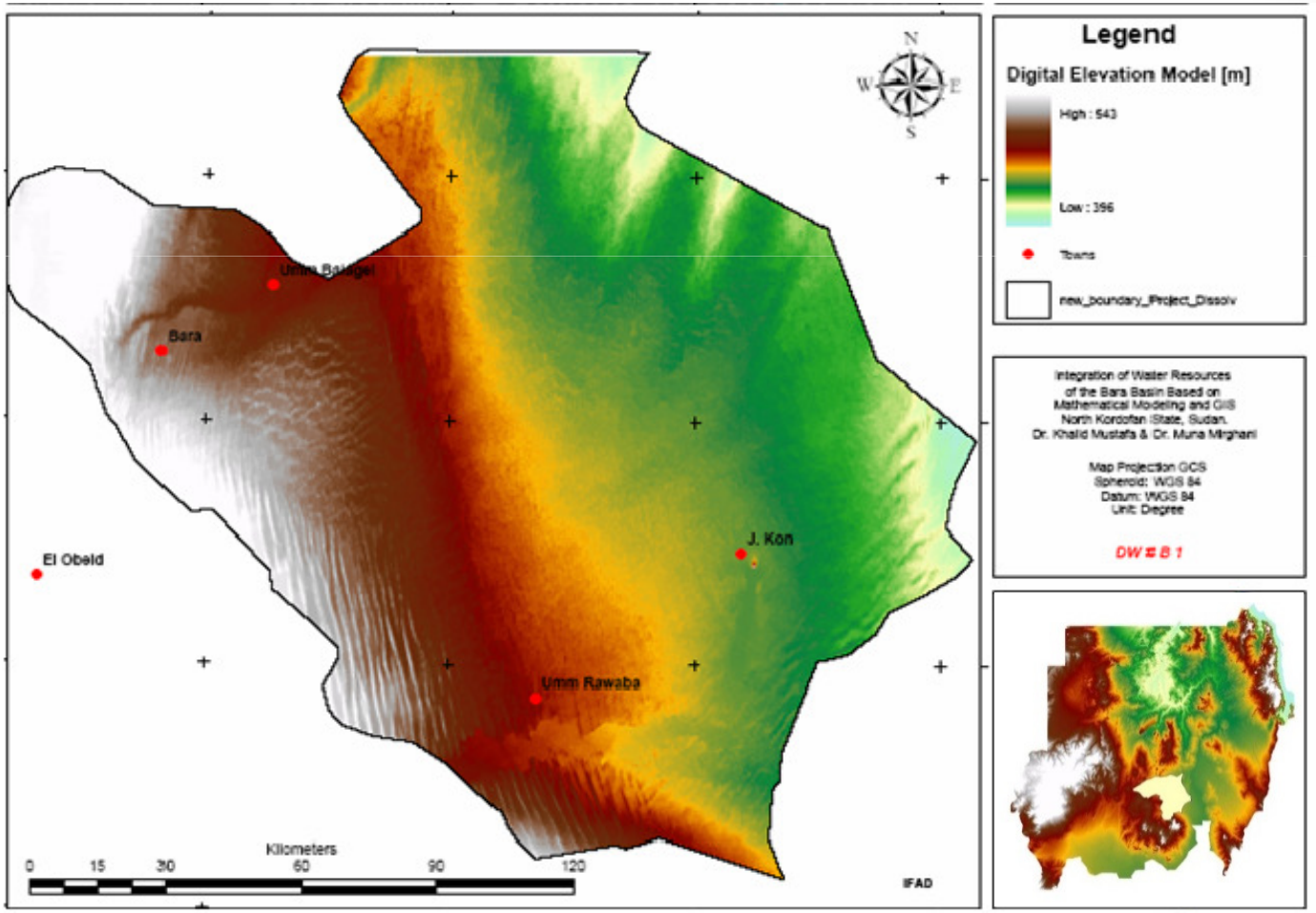


Figure (1): Digital Elevation Model (DEM) map of the study area.

The Study Area

Physiography:

- **The soil of NKS are three types: Sand dunes or Qoz, lighter clays or Gardoud, and heavy clays (IFAD, 2004).**
- **The area extends over two climatic belts in the sub-Saharan region: a semi-arid zone in the north and a poor Savannah in the south.**
- **According to Mukhtar (2006), the current total population of NKS amounts to 2,353,460 persons based on Central Bureau of Statistic (CBS) population projections (2003-2018).**

The Study Area

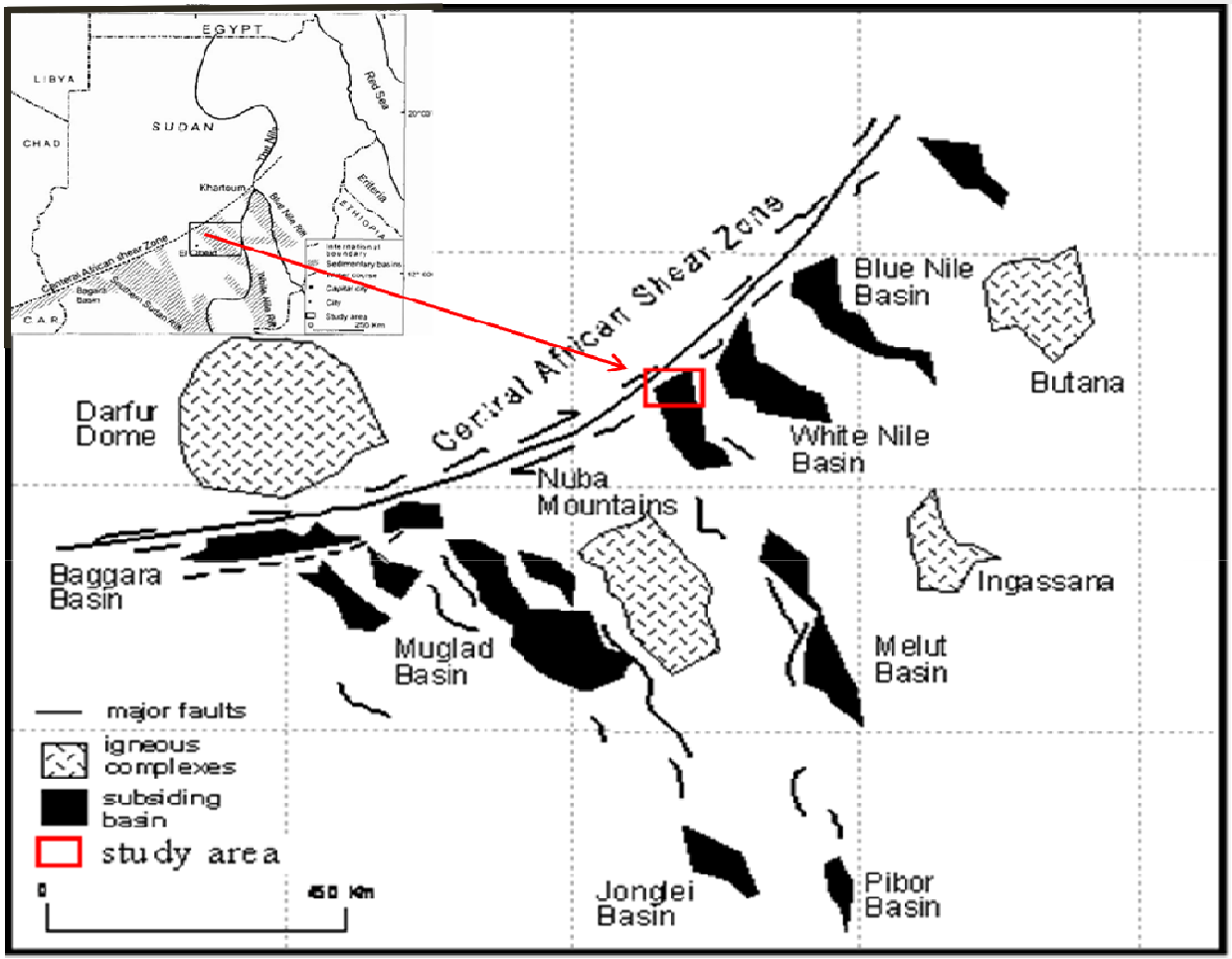
Geology:

- In Mid Miocene, the continental seas had covered the whole region depositing the thick horizontally bedded Nubian sandstone formation.

- The volcano activity, by the End of Mesozoic, had resulted in the creation of the African Rift System with its western limb forming the White Nile (Bara–Um Ruwaba) and the Baggara troughs separated by the Nuba Mountain–Sodiri Mega Anticline, and terminated from the north by the central Africa Fault Zone (CAFZ).

Figure (2):

Location of the study area within the *Central Sudan Rift Basins*, and the principal basins of the Central and Southern Sudan in relation to Central African Shear Zone (RRI, 1990).



The location of the study area is marked by the red square.

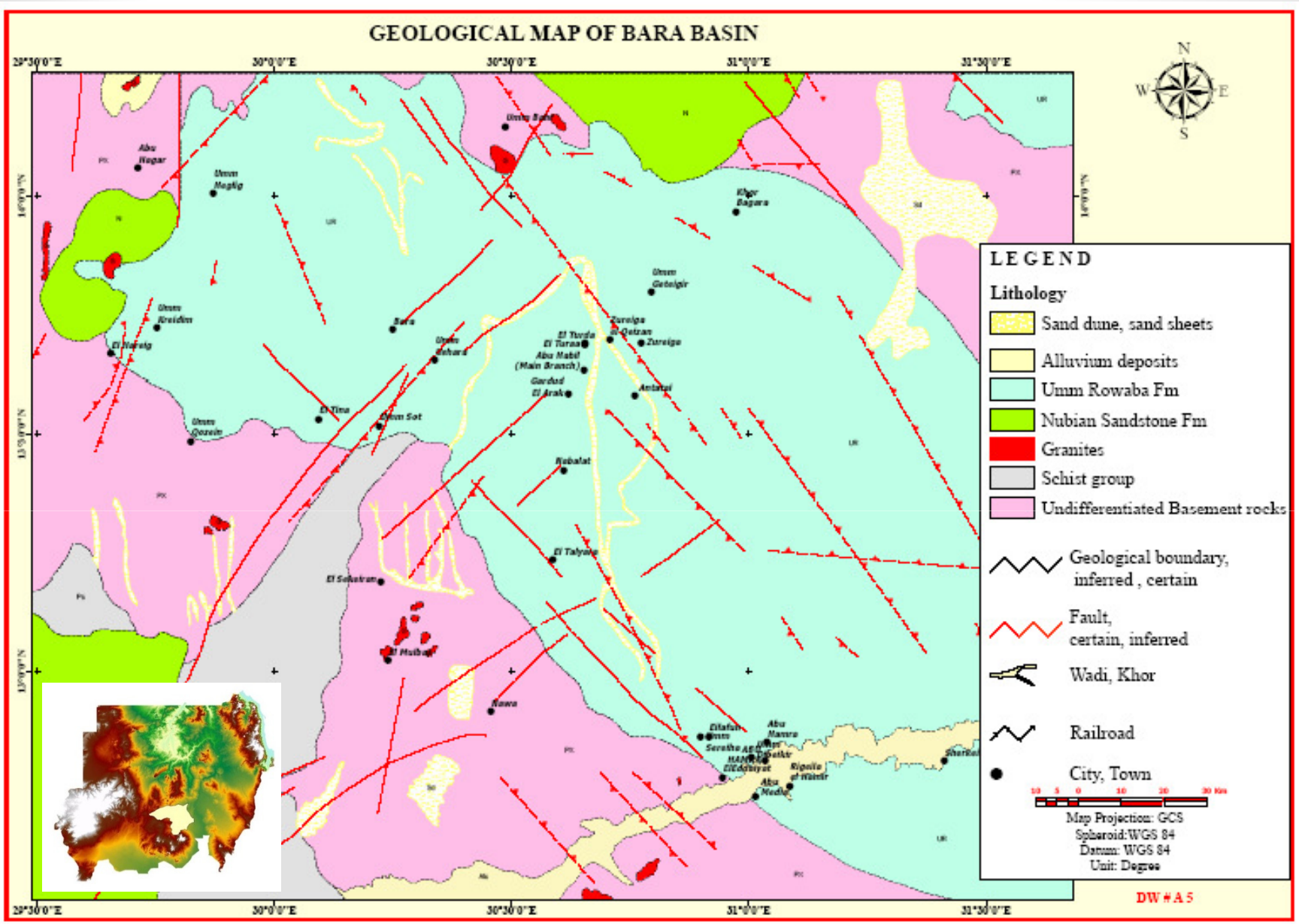


Figure (3): Geological and Structure map of Bara basin (IFAD, 2004.)

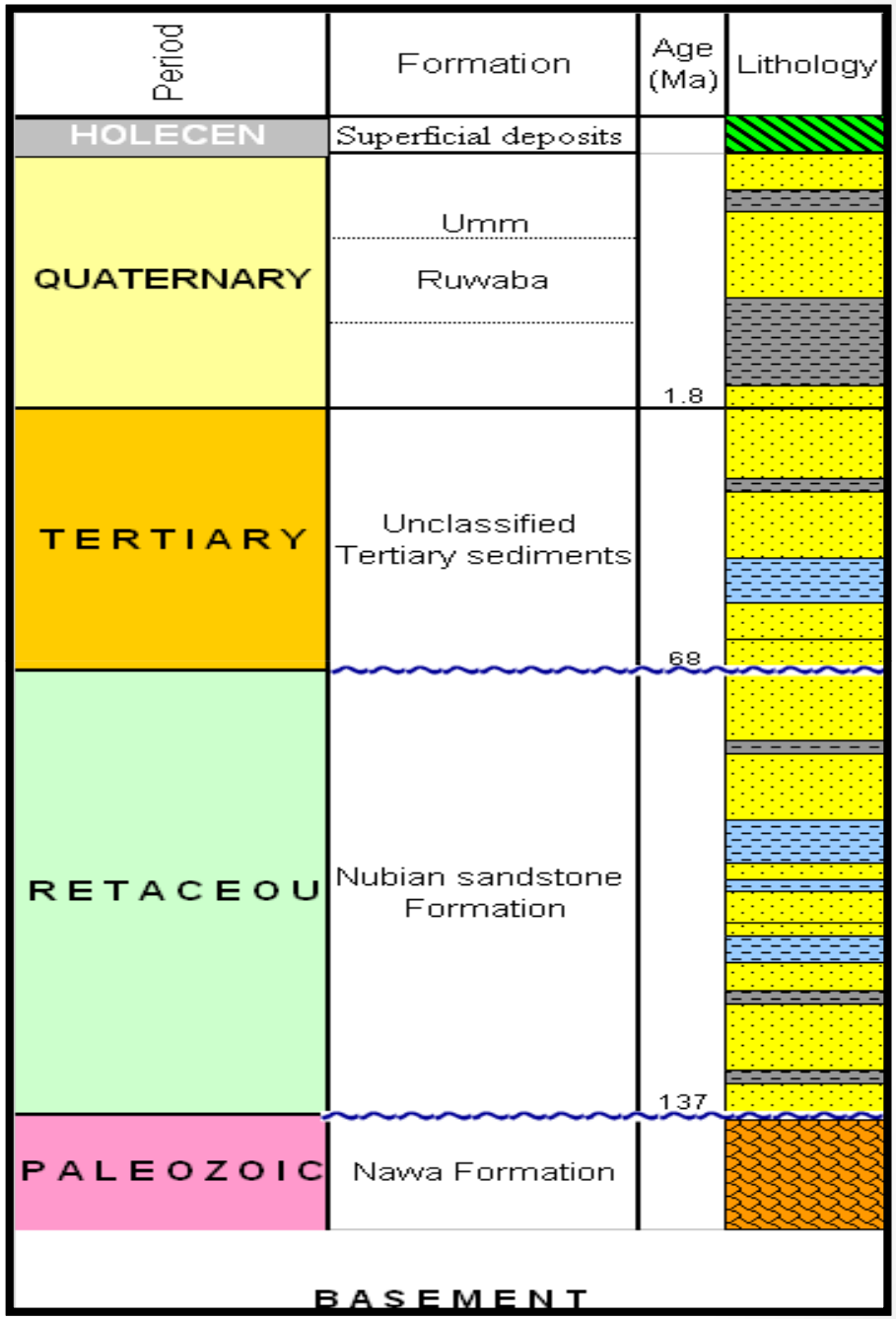
The Study Area

Geology:

- Rodis et.al (1965) described the ground water geology in Kordofan State.
- RRI and GRAS (1990) provide basic study of the geology and petroleum potential of southern, central and eastern Sudan, including Bara basin.
- The main geologic formations covering NKS is itemized in Table-1:

Table (1):

Main geologic formations covering NKS



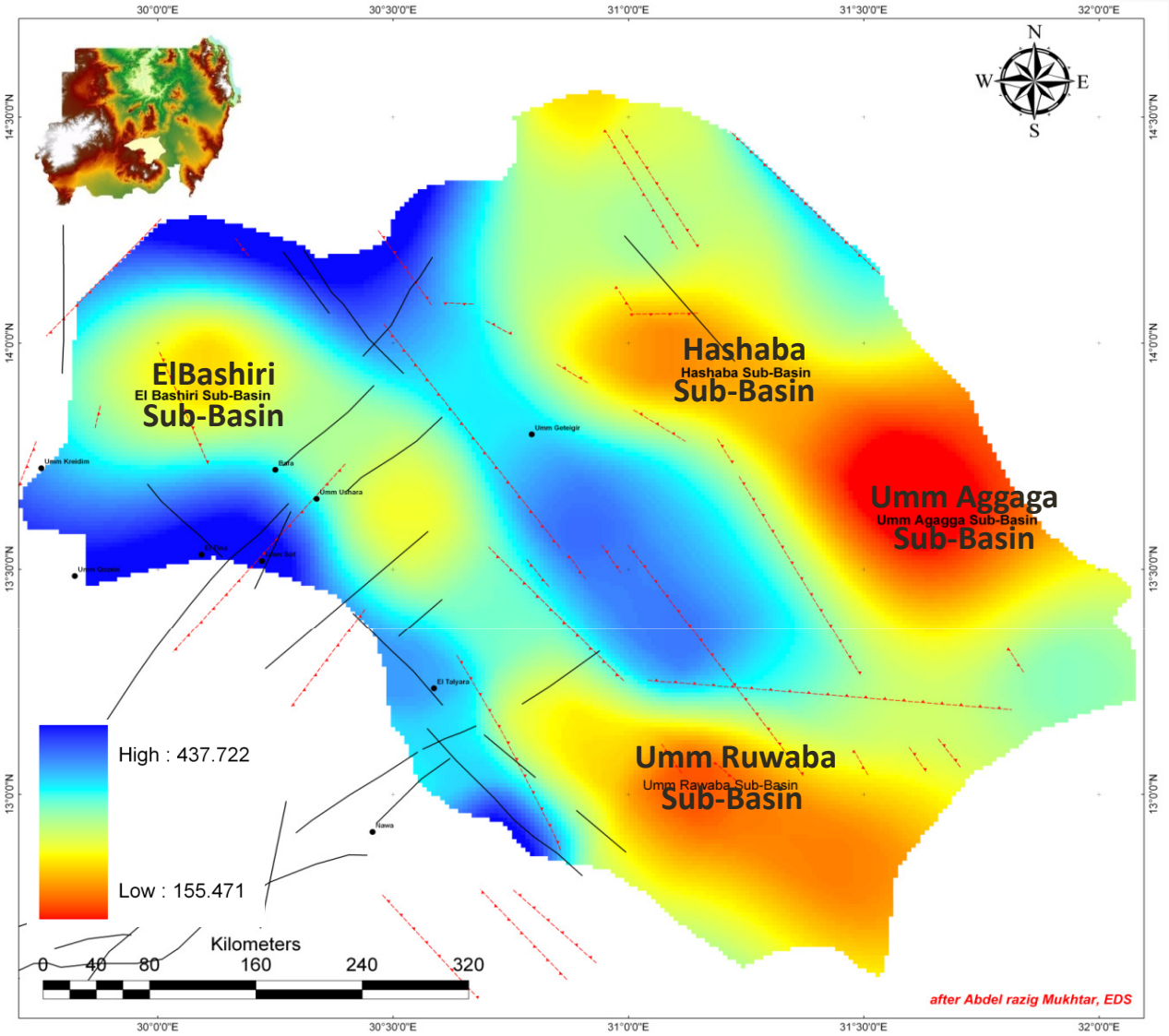


Figure (4): Digital basement terrain model (DBTM) of Bara Basin superimpose by major NW-SE faults and minor NE-SW faults in central Sudan, dividing the basin into four former sub-basins: Hashaba, Umm Aggaga, ElBashiri and Umm Ruwaba sub-basins (after Mukhtar, 2006).

The Study Area

Hydrogeology:

- The annual rainfall increases in amount and duration southward, and ranges from 200 mm to 450 mm.
- The main GW aquifer is the sandstone layers of the Cret. Nubian sediments which extend underlying the Umm Ruwaba sediments.
- GW occurs at depth from 30m to >100m below ground surface generally under free water table conditions.
- Umm Ruwaba sediments are considered as the second important aquifer zone and GW occurs in the sand lenses intercalated with mostly thick clay sediments.

Used Methods

Basis of estimating hydraulic properties from resistivity:

- **The mathematical relations of the electrical transmission and groundwater flow in a conducting porous media is governed by Ohm's law and Darcy's law respectively, both having forms of equation:**

$$j = -\sigma \frac{dv}{dr} \qquad (1)$$

$$q = -k \frac{dh}{dr} \qquad (2)$$

Where j, σ, v, r, q, k, h are respectively the current density (amps per unit area), electrical conductivity (Siemens/m = reciprocal resistivity ρ in ohm.m), electrical potential (volts), distance (meters), specific discharge (discharge per unit area), hydraulic conductivity (or permeability; m/s), and the hydraulic head (m).

Used Methods

Basis of estimating hydraulic properties from resistivity:

- **The electro-hydrological similarity between these two phenomena is widely accepted (Freeze and Cherry, 1979; Fitts, 2002; Singh, 2005).**
- **In a homogeneous and isotropic medium, both the electric current and groundwater flow satisfy the Laplace equation:**

for electrical flow:

$$\frac{d^2v}{dr^2} + \frac{2}{r}\frac{dv}{dr} = 0 \qquad (3)$$

and

for groundwater flow:

$$\frac{d^2h}{dr^2} + \frac{1}{r}\frac{dh}{dr} = 0 \qquad (4)$$

Used Methods

Basis of estimating hydraulic properties from resistivity:

- **For a point current source, the solution of equation (3 &4) in a semi-infinite, homogeneous medium (hemispherical earth):**

for electrical flow is: $$V = \frac{lI}{2\pi}\frac{1}{r} \qquad (5)$$

and

for hydraulic flow is: $$h = \frac{Q}{2\pi T}\ln(r) \qquad (6)$$

Used Methods

Basis of estimating hydraulic properties from resistivity:

- Transmissivity of an aquifer of saturated thickness b, is then expressed by

$$T_r = kb \qquad (7)$$

- Such that the laplacian equation becomes:

$$h = \frac{Q}{2\pi kb} \ln(r) \qquad (8)$$

- Generally, since larger connected pores make better flow features for both water & electric current, it is expected that there should be some relation between electrical and hydraulic parameters (Singh, 2005).

Used Methods

Data acquisition and interpretation:

- **Thirty five vertical electrical soundings (VES) were carried out in ElBashiri and Umm Ruwaba sub-basins by IFAD 2004 using:**
  - **Schlumberger electrode spreading**
  - **Maximum current electrode separation (AB) up to 1.8 km.**
  - **Most VESs were conducted nearby existing boreholes for correlation purposes.**
  - **VES interpretation using IX1D computer-assisted program.**
  - **This estimates for each VES the layers thickness and their true resistivity values.**

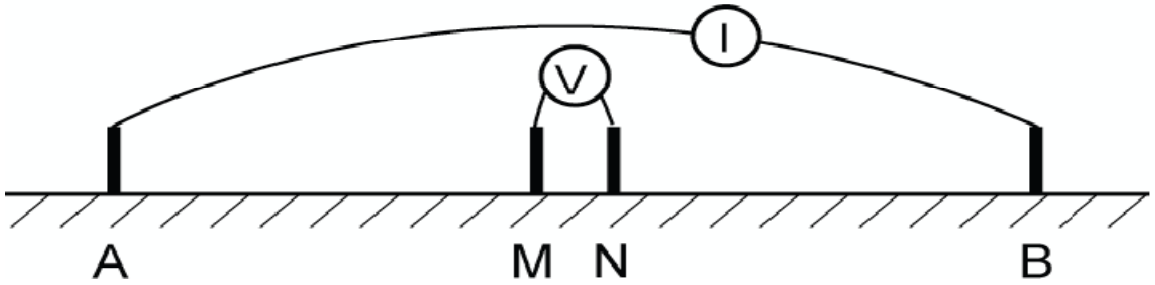


Figure (5): Schlumberger configuration

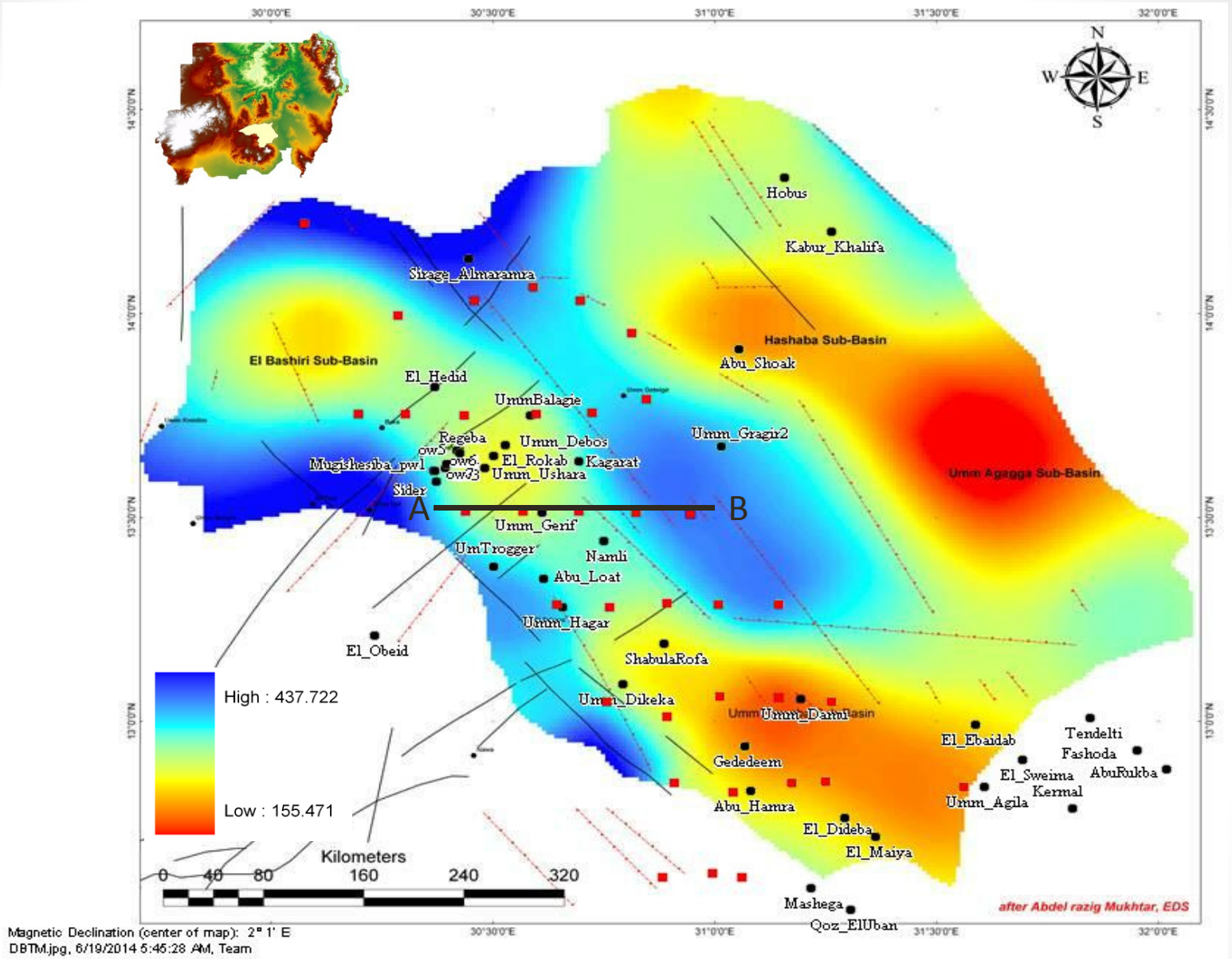


Figure (6): Locations of VES are shown in red squares and the pumping wells are shown in black circles. AB is the geoelectric section across selected VESs.

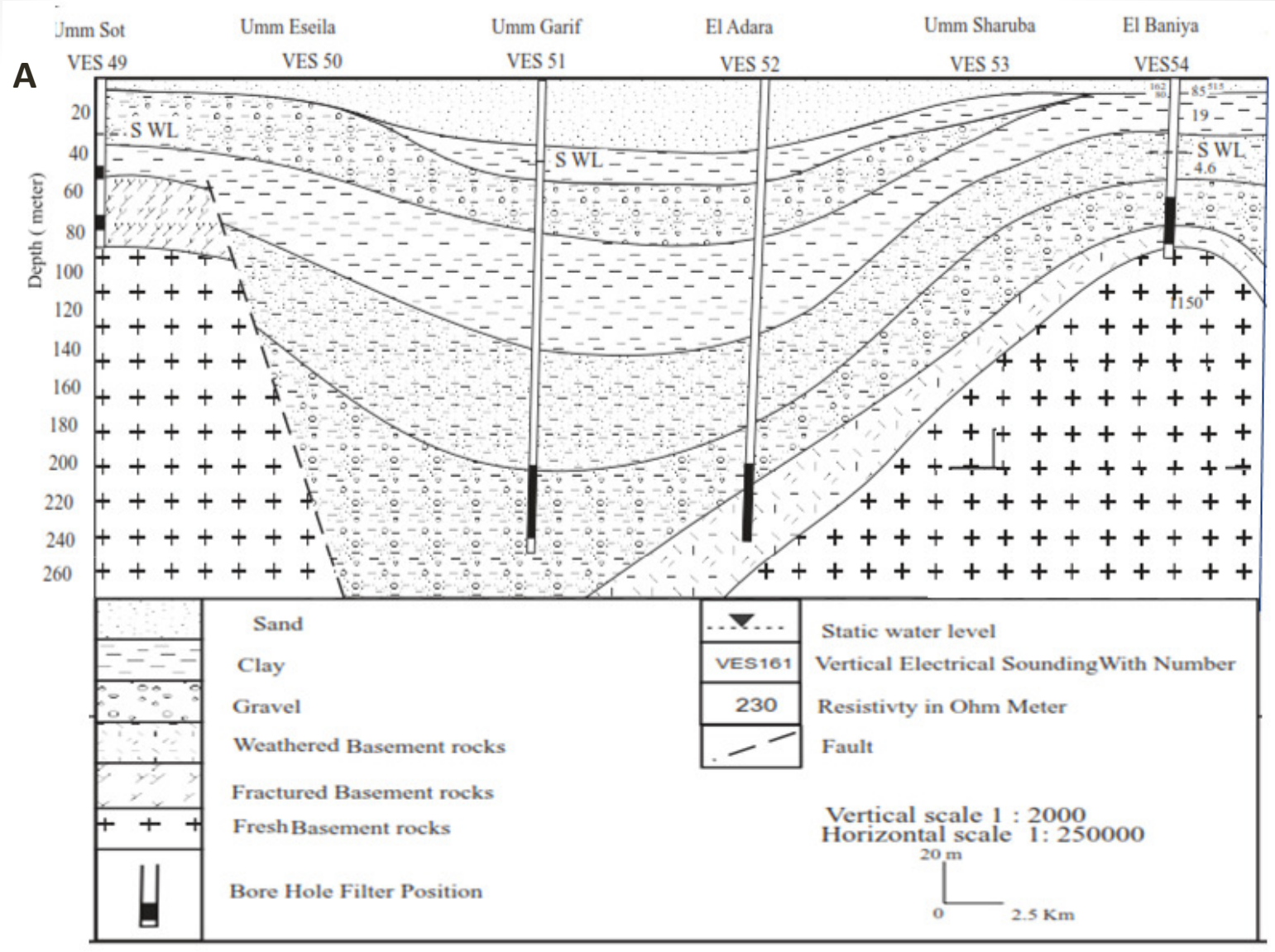


Figure (7): Cross section shows the stratigraphy along a number of electrical soundings (VES) and the adjacent boreholes wells (IFAD, 2004).

Table (2): Based on VES results and wells calibration (from WES 2004) in the area, the following resistivity ranges and the corresponding lithologies are adopted for this study:

Lithology	Resistivity (Ω.m)
Running Qooz sands	50 – 300
Surface clay, sand, gravel	30 – 160
Subsurface mudstones (saturated)	5 – 30
Subsurface Sandstone (saturated)	10 – 100
Fractured basement (saturated)	10 – 80
Fresh Basement Complex	> 300

Used Methods

Data acquisition and interpretation:

- **From the true resistivity data, it was possible to compute, for every VES, the following (Singhal et al., 1998).:**

the longitudinal resistivity:

$$\rho_L = \frac{\sum h_i}{\sum h_i / \rho_i} \qquad (9)$$

the transverse resistivity:

$$\rho_T = \frac{\sum h_i * \rho_i}{\sum h_i} \qquad (10)$$

Where h_i and ρ_i are layer thickness and resistivity respectively

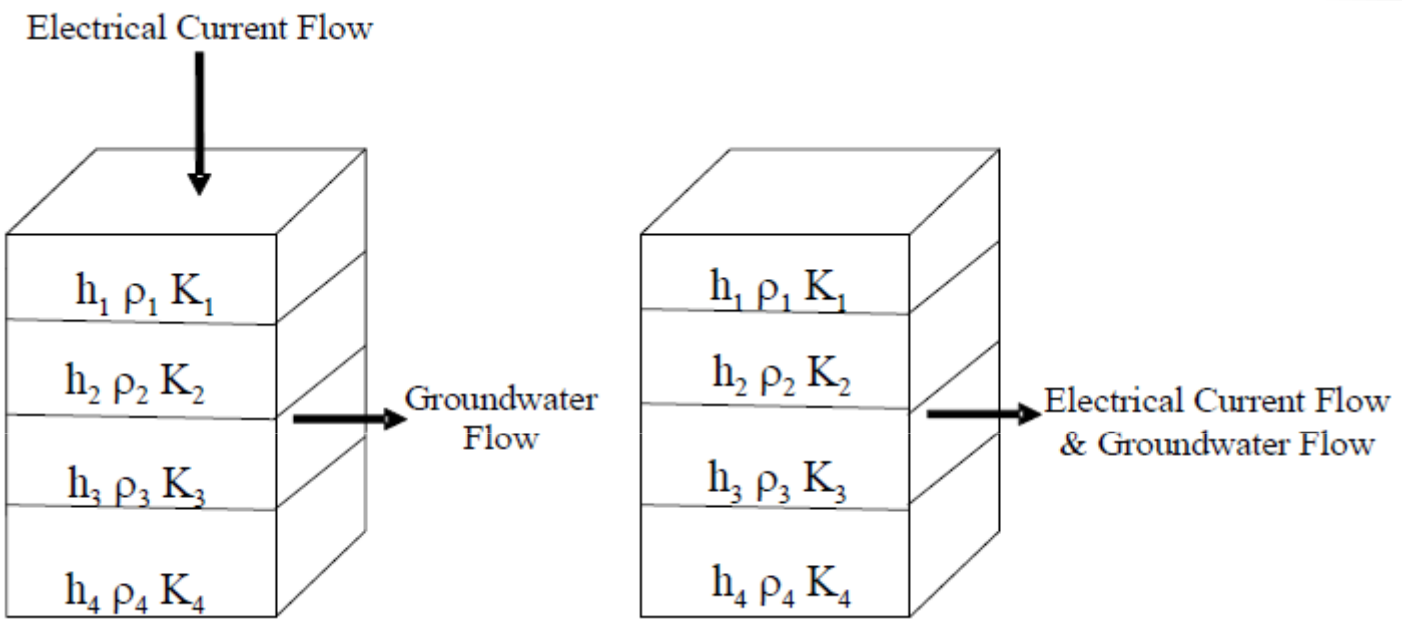


Figure (8): Layered model showing transverse and longitudinal current flow.

Used Methods

Data acquisition and interpretation:

- **Archie's Law (1942) relates the layer resistivity derived from geoelectric field curve to pore water resistivity and the porosity of the porous skeleton:**

$$F = \frac{\rho_o}{\rho_w} = a\Phi^{-m} \qquad (11)$$

where F is the resistivity formation factor which is constant for pure sands, ρ_o, is the resistivity of the saturated rock at each sounding position, ρ_w is the water resistivity and Φ is the formation porosity, *a* and *m* are empirically derived constants related to rock type.

Used Methods

Data acquisition and interpretation:

- **The modified aquifer resistivity (ρ`) includes the changes in aquifer material and the interconnected pores tortuosity. The modification factor is a ratio of average aquifer water resistivity and aquifer water resistivity for each VES .**

$$\rho` = \rho_o \frac{\overline{\rho_w}}{\rho_w} \qquad (12)$$

According to Singal and SiriNiwas (1985), Where ρ` is the modified aquifer resistivity, ρ_w is average water resistivity, and ρ_w is the water resistivity.

Used Methods

Data acquisition and interpretation:

- **Transmissivity (T) is computed from the transverse resistance (R) or using the modification factor as:**

$$T = (k\sigma)R = (k\sigma`)R` \qquad (13)$$

Where *k* is the hydraulic conductivity, *σ* is the electrical conductivity, and R is the transverse resistance,

and, $$\sigma` = \sigma \frac{\overline{\rho_w}}{\rho_w}$$

and, $$R` = R \frac{\overline{\rho_w}}{\rho_w}$$

Results and Discussion

- **The study area consists of a maximum 5 layers where the aquifer thickness is highly variable.**

- **The water level and the electrical conductivity data of 17 pumping wells (WES, 2004) in the vicinity of the study area were collected to determine the formation factor.**

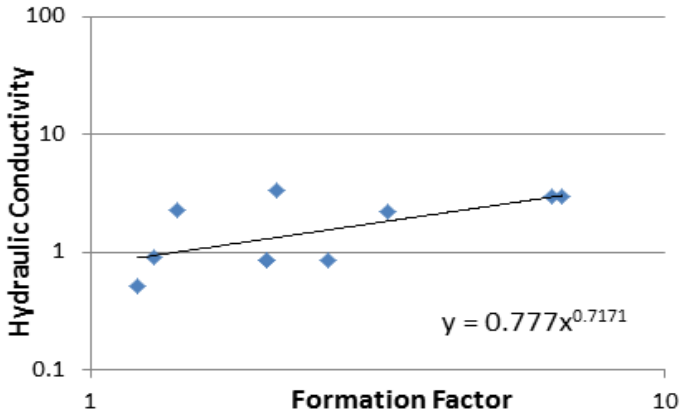
St. No.	VES No.	Formation Factor	Hydraulic Conductivity (m/d)	St. No.	VES No.	Formation Factor	Hydraulic Conductivity (m/d)
1	15	**4.802**	**0.031**	9	33	**2.064**	**0.12**
2	16	**3.822**	**0.031**	10	51	**3.2844**	**2.2**
3	17	**4.187**	**0.19**	11	52	**2.025**	**0.86**
4	28	**6.604**	**3**	12	53	**2.025**	**0.86**
5	27	**6.35**	**3**	13	126	**2.592**	**0.86**
6	29	**2.706**	**0.067**	14	127	**1.2865**	**1**
7	31	**1.208**	**0.52**	15	128	**1.411**	**2.3**
8	32	**2.352**	**0.12**	16	129	**2.108**	**3.3**

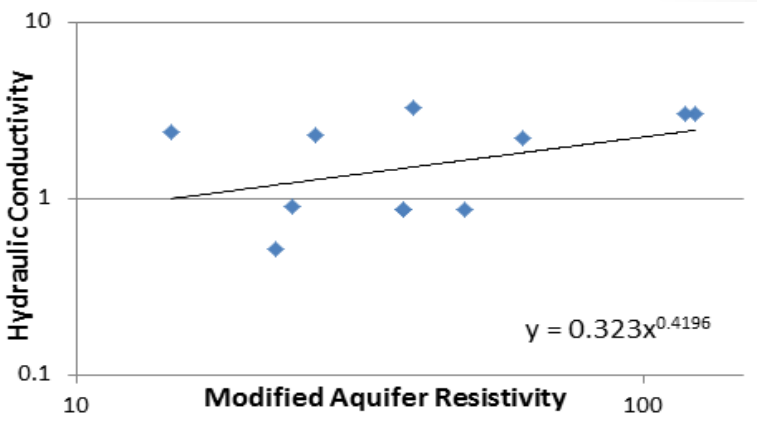
Table (3): K from TPW and F from resistivity data

Results and Discussion

- **Three types of empirical relations have been established between(Fig.9).:**
  - ***hydraulic conductivity (k) and formation factor (F),***
  - ***hydraulic conductivity (k) and modified aquifer resistivity (ρ'),***
  - ***and the relation between transmissivity (T) and transverse resistance(R_T).***
- **These relations are restricted to unconsolidated sediments where the aquifer is anisotropic due to sediments layering.**

Results and Discussion





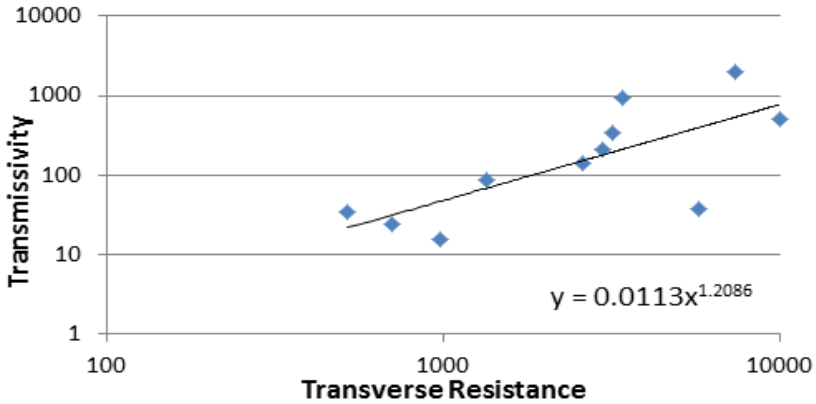


Figure (9): Empirical relations between hydraulic conductivity and formation factor, hydraulic conductivity and modified aquifer resistivity, and transmissivity and transverse resistance.

Results and Discussion

$$K = 0.777 * F^{0.7171} \quad (14)$$

$$K = 0.323 * \rho_{\text{mod}}^{0.4296} \quad (15)$$

and ,

$$T = 0.011 * R_T^{1.2086} \quad (16)$$

- **The three empirical math. relations between K and F, K and ρ_{mod} , and T and R_T .**
- **The calculated T and K values from equations (16 & 7) are generally close to the measured values from TPW in the area.**

Results and Discussion

Table (4): Results of vertical electrical soundings (VES) and pumping test for the study area.

EVALUATED PARAMETERS	WELL 13	WELL 11	WELL 14	WELL 37	WELL 4	WELL 18	WELL 23	WELL 24	WELL 22	WELL 17	0w5	AVERAGE
	Aldibeba	AbuHamra	UmDamu	UmmDikeka	AbuLoat	Sider	Umm Gerif	Kaggarat	ElHadid	UmDebos	ow5	
Aquifer thickness (b) in m	26	66	98	45	95	70	70	20	70	33	64	59.8
Transmissivity (T) in m^2/d	20.3	0.6	613	11	5.2	445	35.7	35.7	176	445	445	203
Hydraulic Conductivity (k) in m/d	0.031	0.19	3	0.52	0.12	2.2	0.86	0.86	1	2.3	3.3	1.31
Water Resistivity (ρ_w) in Ω.m	10.2	12.7	7.9	13.2	20.8	14	12.3	12.3	24.1	24.1	16.1	15.3
Formation Factor	3.8	4.2	6.3	1.2	2.4	3.2	2.6	2.1	1.3	1.4	2.2	2.8
Modified Aquifer Resistivity (ρ`) in Ω.m	71.3	78.1	118.4	22.5	44	61.3	48.3	37.8	24	26.3	39.3	52
Modified Aquifer Conductivity (σ`) in S/m	0.01403	0.0128	0.00845	0.04444	0.0227	0.0163	0.0207	0.0265	0.0417	0.038	0.0254	0.0246
Transverse Resistivity (ρ_T)	292.85	87	49.84	173.11	91.06	42.25	142.67	25.93	48.869565	35.15	158.6522	104.3
Longitudinal Resistivity (ρ_L)	89.48	67.9	27.41	27.13	34.01	31.34	40.45	12.06	7.28	10.9	13.24	32.84
Modified Transverse Resistance (R`)	12685.2	7711.5	7316.6	3332.8	7058.6	3589.8	13751.6	714.1	689.6	496	3344.4	5517.3
Calculated Transmissivity (T) in m^2/d	16.8	37.13	947	139	14.1	208	508.9	33.8	15.7	23.7	342.1	208
Calculated Hydraulic Conductivity (k) in m/d	0.6462	0.5626	3	3.0889	0.1484	2.9714	7.27	1.69	0.2243	0.7182	5.34	2.3

Results and Discussion

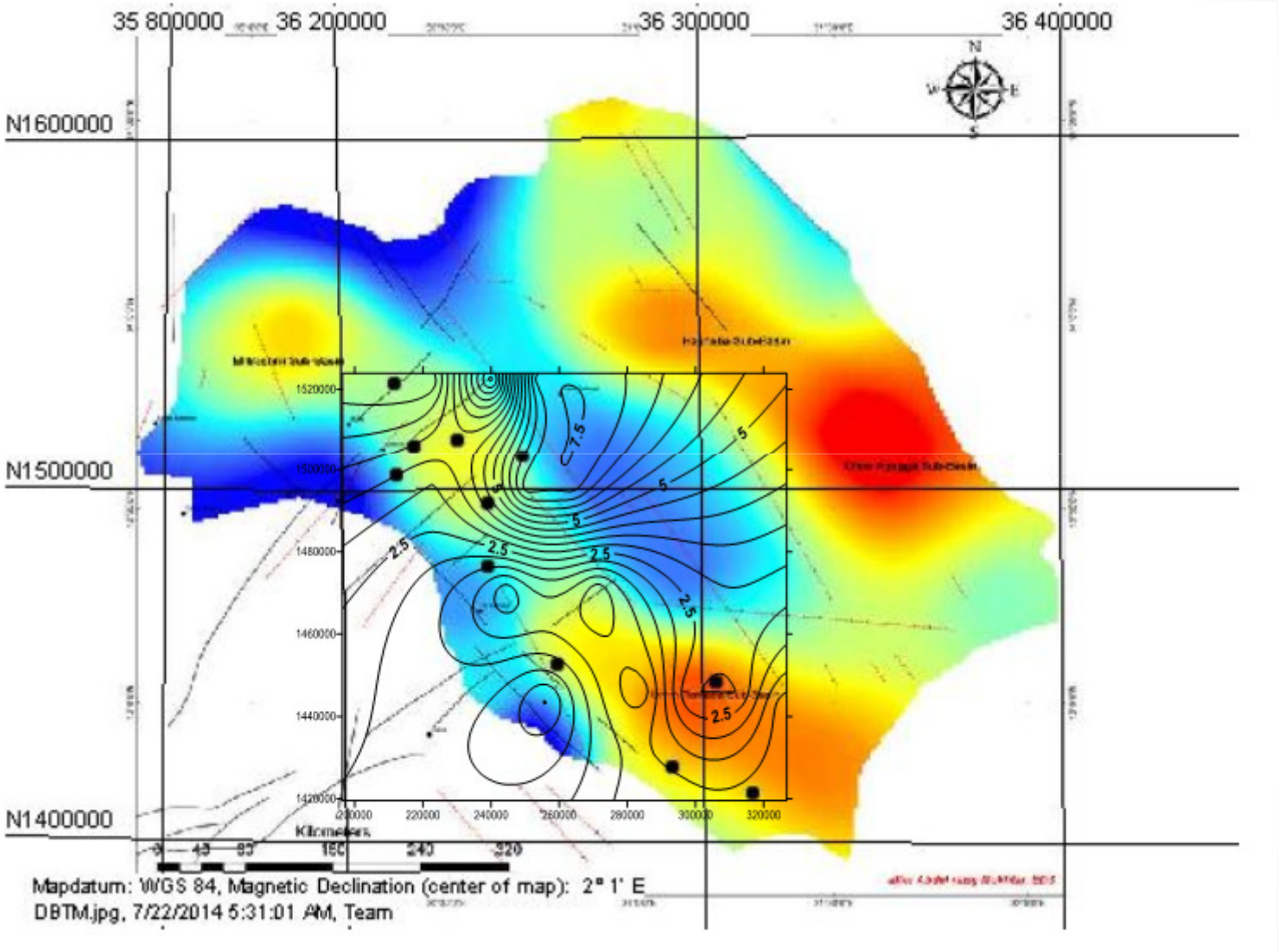


Figure (10): Calculated hydraulic conductivity contour map of the study area.

Results and Discussion

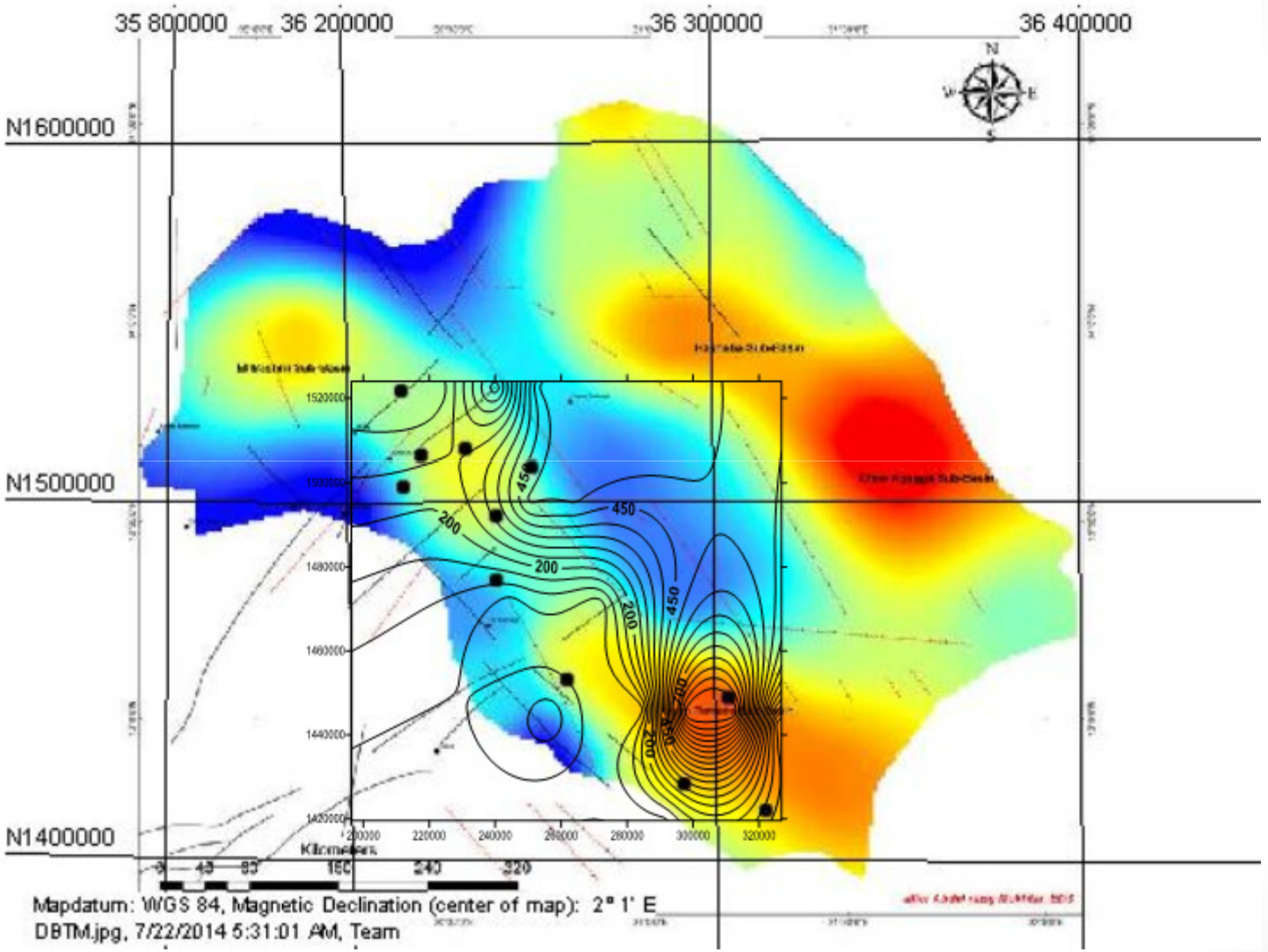


Figure (11): Calculated transmissivity contour map of the study area.

Results and Discussion

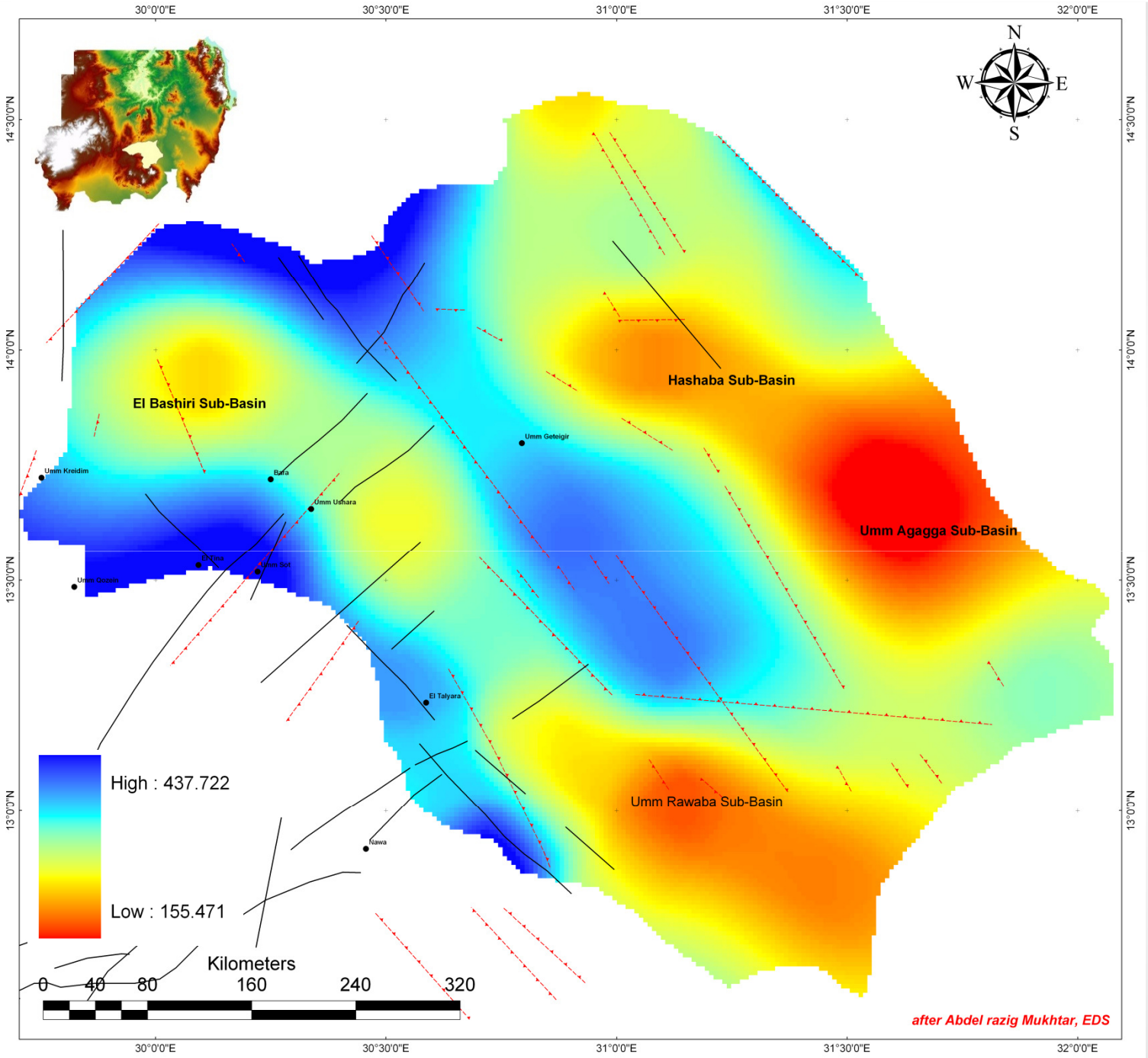
- **The calculated hydraulic parameters using the relations derived from the geoelectric data compared to TPW data in this study:**

	TPW Data	Derived Calculations
Hydraulic conductivity (K)	0.031 - 3.3 m/d **avrg: 1.31 m/d**	0.15 – 7.3 m/d **avrg: 2.3 m/d**
Transmissivity (T)	11 – 613 m^2/d **avrg: 203 m2/d**	14 – 947 m^2/d **avrg: 208 m2/d**

- **This study improve the reliability of the geoelectrical methods can be used, for qualitative measurements as well as for quantitative estimates of aquifer properties.**

- **This derivation technique reduces additional disbursements for pumping tests and offers an alternative approach for estimating the hydraulic characteristics of an alluvial aquifer.**

thank you
for
your attention.


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30°30'0"E
31°0'0"E
31°30'0"E
32°0'0"E
14°30'0"N
14°0'0"N
13°30'0"N
13°0'0"N
N
W
E
S
El Bashiri Sub-Basin
Hashaba Sub-Basin
Umm Agagga Sub-Basin
Umm Rawaba Sub-Basin
Umm Geteigir
Umm Kreidim
Bara
Umm Ushara
El Tina
Umm Sot
Umm Qozem
El Talyara
Nawa
High : 437.722
Low : 155.471
Kilometers
0 40 80 160 240 320
after Abdel razig Mukhtar, EDS

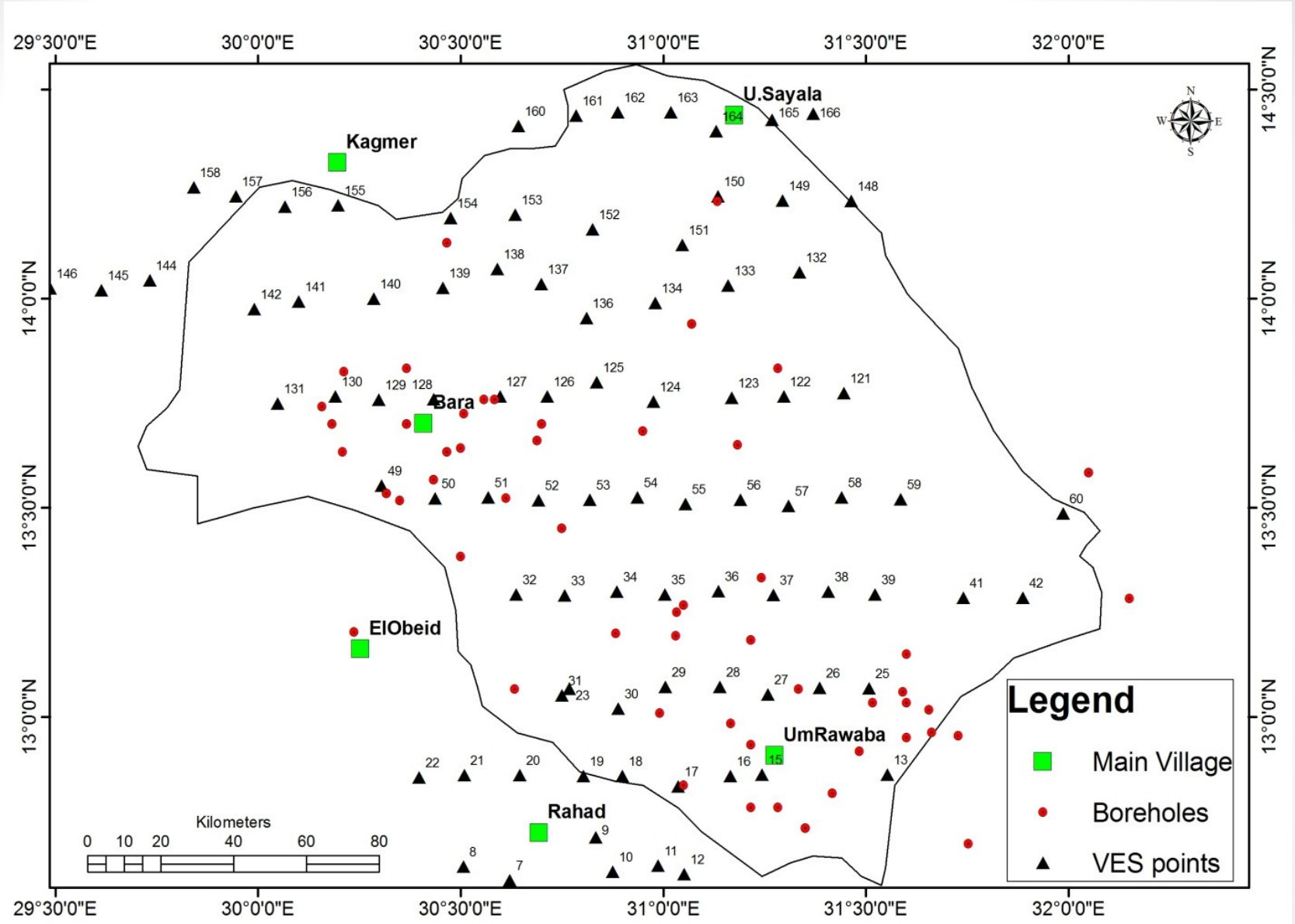
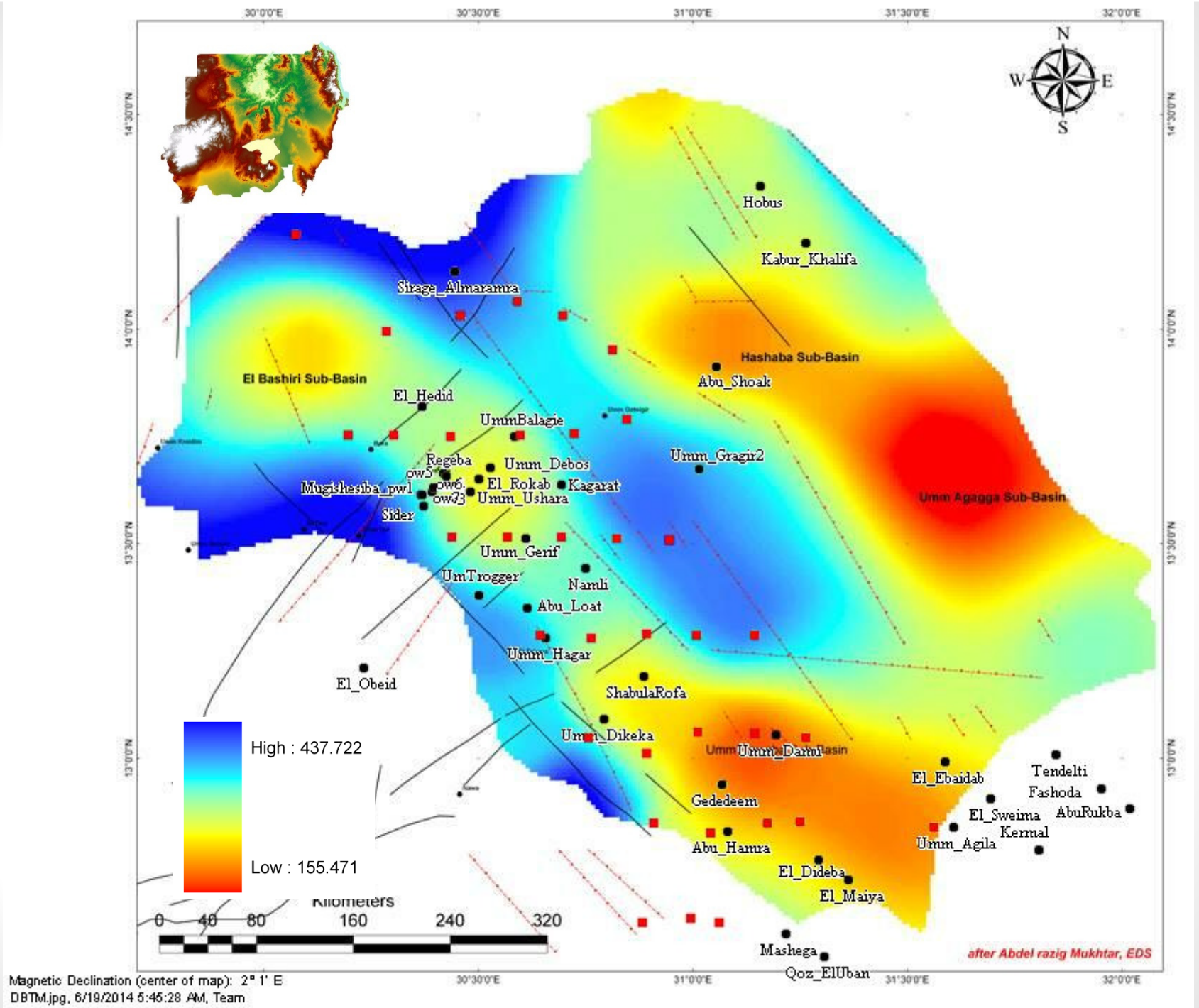
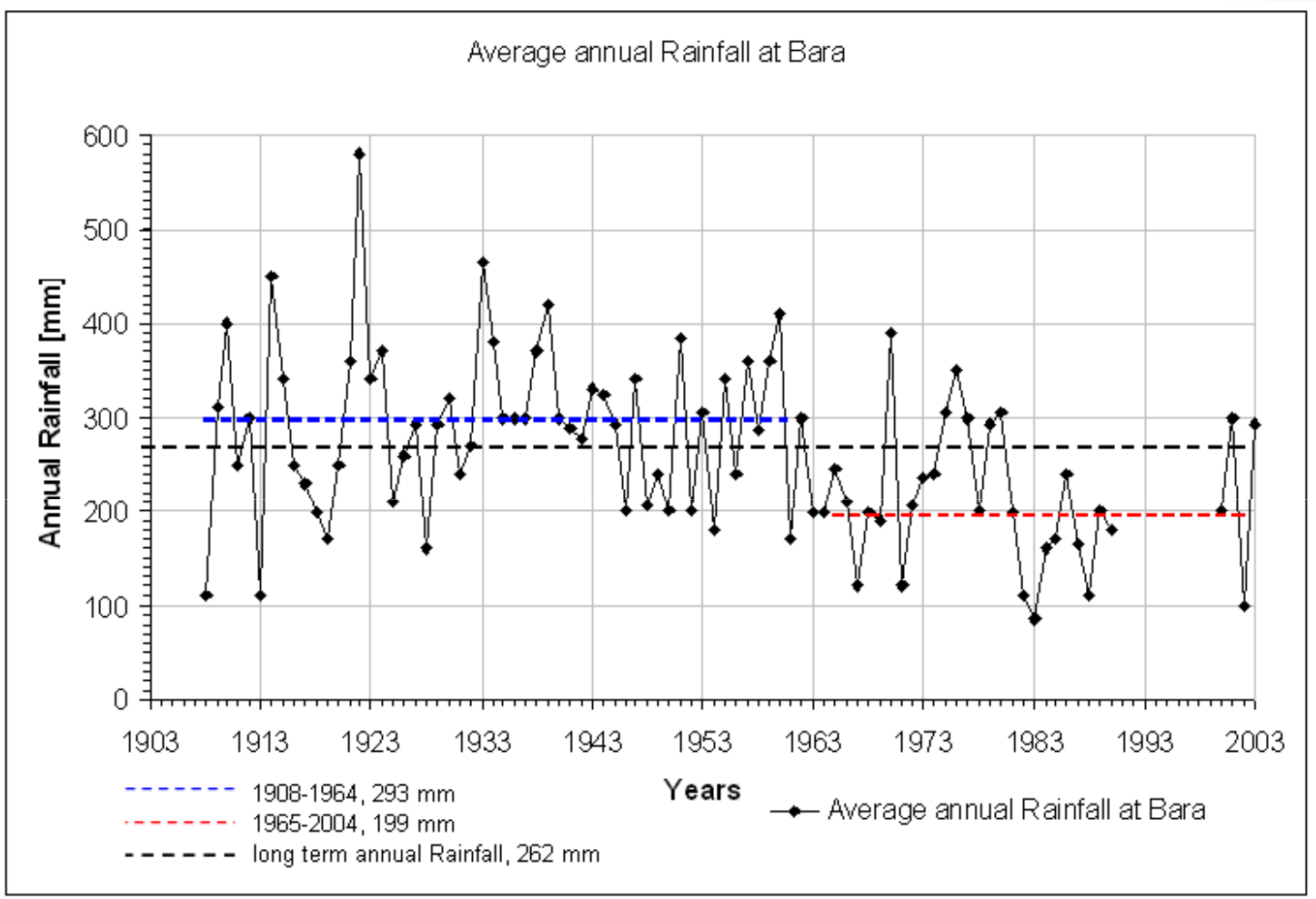


Figure (): Shows the location map of vertical electrical sounding (VESES), and boreholes locations


30°0'0"E
30°30'0"E
31°0'0"E
31°30'0"E
32°0'0"E
14°30'0"N
14°0'0"N
13°30'0"N
13°0'0"N
N
W
E
S
Hobus
Kabur_Khalifa
Sirage_Almaramra
Hashaba Sub-Basin
El Bashiri Sub-Basin
Abu_Shoak
El_Hedid
UmmBalagie
Umm_Gragir2
Regeba
Umm_Debos
ow5
ow6
ow23
El_Rokab
Kagarat
Mugishesiba_pw1
Umm_Ushara
Umm Agagga Sub-Basin
Sider
Umm_Gerif
UmTrogger
Namli
Abu_Loat
Umm_Hagar
El_Obeid
ShabulaRofa
Umm_Dikeka
Umm Umm_Dam Basin
El_Ebaidab
Tendelti
Fashoda
AbuRukba
El_Sweima
Kermal
Gededeem
Umm_Agila
Abu_Hamra
El_Dideba
El_Maiya
Mashega
Qoz_ElUban
High : 437.722
Low : 155.471
Kilometers
0 40 80 160 240 320
after Abdel razig Mukhtar, EDS
Magnetic Declination (center of map): 2° 1' E
DBTM.jpg, 6/19/2014 5:45:28 AM, Team



Average annual rainfall at Bara town

Description	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Average Rainfall mm	0.0	0.0	0.0	1.3	12.4	32.9	120.6	132.6	56.8	10.7	0.2	0.0	**367.5**
Maximum Rainfall mm	0.0	0.0	0.0	25.0	72.0	141.0	397.0	425.6	161.5	67.0	15.0	0.0	**982.6 (1946)**
Minimum Rainfall mm	0.0	0.0	0.0	3.9	12.0	16.0	22.0	10.5	2.0	0.0	0.0	0.0	**66.4 (1984)**
St.Dev.	0.0	0.0	0.0	4.1	15.8	27.0	63.4	67.9	34.0	12.4	1.7	0.0	**117.0**
Rainy Days No.	0.0	0.0	0.0	0.0	0.0	3.0	13.0	10.0	4.0	0.0	0.0	0.0	**30.0**
Temperatures													
Mean	22.0	22.8	27.0	29.6	31.5	30.7	28.1	26.6	27.6	28.7	25.6	22.5	**26.8**
Maximum	30.5	31.0	35.6	38.2	39.0	37.2	33.9	31.3	33.7	36.1	33.8	30.8	**36.7**
Minimum	13.5	14.5	18.2	21.0	24.0	24.2	22.8	21.8	21.5	21.2	17.5	14.1	**19.5**
Mean Relative Humidity	32.0	27.0	21.0	25.0	36.0	50.0	64.0	73.0	65.0	48.0	30.0	31.0	**42.0**
Sunshine %	91.0	91.0	91.0	83.0	76.0	65.0	56.0	55.0	69.0	80.0	90.0	94.0	**78.0**
Vapour Pressure [Mbs]	6.2	5.5	5.7	7.6	12.6	17.8	22.0	24.0	21.6	14.5	8.5	7.0	**12.7**
Wind Velocity [m/s]	2.5	2.8	2.5	2.2	2.5	2.8	2.8	2.2	1.9	2.2	2.5	2.5	**2.3**
Evapotranspiration [mm/d]	5.8	6.8	7.5	7.3	7.6	6.8	5.5	4.6	5.2	6.2	6.4	5.6	**6.3**
Evapotranspiration [mm/m]	**179.8**	**190.4**	**232.5**	**219.0**	**235.6**	**204.0**	**170.5**	**142.6**	**156.0**	**192.2**	**192.0**	**173.6**	**2,288.2**

Climatological Data (1912-1993), Umm Ruwaba Station-Abu Habil Basin.

SOURCES: Crop Ecology & Genetic Resources Unit, Plant Production & Protection Division, FAO, North Kordofan Rural Development Project-(IFAD). And Metrological Departments, Umm Ruwaba & Khartoum.