Topographic attributes control groundwater flow and groundwater salinity of Al Ain, UAE: a prediction method using remote sensing and GIS

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Abstract

In arid regions, over pumping and extraction of groundwater in excess of recharge has resulted sharp depleting in groundwater quantitatively and qualitatively. The effect of topographic attributes on groundwater accumulation and groundwater salinity was investigated in the southwest part of Al Ain, Abu Dhabi using Digital Elevation Model (DEM). Seven topographic attributes, such as topography, slope, aspect, relief, catchment area and drainage network were calculated. The results showed that the area is drained by 3 main basins emerging from Hafeet Mountain and drain southwesterly toward Ain Al Fayda and sand dunes. The results also showed all topographic attributes and hydrological elements are strongly structural controlled by NW and NNE trending fault zones. Spatial correlation was performed to correlate topographic attributes and hydrological data collected from groundwater samples. The result showed strong correlation between flow accumulation and groundwater salinity and topographic attributes and irrigation areas. These findings prove the usefulness of the proposed methods in predicting and identifying sites of high groundwater accumulation and groundwater salinity in arid region.

Keywords Hafeet Mountain, Al Ain, UAE, Groundwater, Remote sensing

1. Introduction

Groundwater is the main source to land development in the Arabian Gulf countries particularly in the United Arab Emirates (UAE). Recently, groundwater quality varies widely in the UAE including study area because of the presence of saline groundwater containing more than 1000 mg/l of total dissolved solids (JICA 1996, Murad 2007). The reasons of an increase in groundwater salinity are numerous, including aridity, the nature of the aquifer rocks, groundwater recharge, and aquifer thickness and over pumping and excessive consuming of groundwater in the Abu Dhabi Emirate, UAE (Todd 1995, JICA 1996, Murad 2007, Rathore *et al.* 2008). The tectonic activity during late cretaceous has led to deformation, displacements and thrusting in the hard rocks of Oman and Hafeet mountainous (Glennie *et al.* 1974, Finzi 1973, Hunting 1979). Several studies have been made to investigate the influence of geological structures on groundwater accumulation and groundwater quality using remote sensing and geographic information system (GIS).

With the widespread of remote sensing data, various techniques have been applied using integration of various geomorphometric, geological and hydrological parameters not only to delineate new groundwater potential zones, but also solve other problems related to groundwater quality (Prasad *et al.* 2007). Jaiswal *et al.* (2003) have used GIS technique for generation of groundwater prospect zones towards rural development. Krishnamurthy *et al.* (1996), Murthy (2000), Obi Reddy *et al.* (2000), Pratap *et al.* (2000), Singh and Prakash (2002), have used GIS to delineate groundwater potential zone. Srinivasa Rao and Jugran (2003) have applied GIS for processing and interpretation of groundwater quality data. GIS has also been considered for multicriteria analysis in resource evaluation.
In the UAE, Khalifa (1997), Al Nuaimi (2003) and Murad *et al.* (2012) reported an increase in the groundwater salinity from east to west and from north to south in Al Ain areas and fresh water at the foot of Oman and Hafeet Mountains, suggesting the change in groundwater system in the last decade. Therefore, the present study was carried out at the foot and western limb of Hafeet Mountain.

In order to predict and identify the relationship between topographic attributes and groundwater salinity and flow accumulation, geomorphometric, geological and hydrological thematic maps (factors) were calculated from DEM and spatial correlation was conducted. Validation of the method was performed by comparing the hydrological data collected from groundwater samples colleted, from groundwater wells with results of the present study (Murad *et al.* 2012).

2. Study area

The study area is stretched from 55° 42´ 00" E to 55° 45′ 36" E and located in the southwest part of Al Ain, UAE. The study area is part of the western limb of Hafeet anticline faulted fold and covered by gravel. It comprises Zakher and Neima areas to the north, Mubazarah and Hafeet Mountain to the east and Ain Al Faydah and Sabkha area to the west (Figure 1). The area belongs to arid region with mean annual rainfall of 96.4 mm (Al Nuaimi 2003).

2.1 Geology and hydrology

The main feature in the study area is the Haffet Mountain. It is composed mainly of carbonate and evaporatic rocks such as limestone, dolomite and gypsum (Garamoon 1996). The extensive history of deformation and karstfication in the south-west part of the study area has destroyed the primary porosity which occurred within the shallow alluvial aquifer. The geological structures that control Hafeet Mountain have significant impact on the hydrology of the study area (Hamdan and Bahr 1992). Their trends are found to be in the NNW-SSE direction and parallel to the fold axis of Hafeet Mountain (Woodward and Al Sharhan 1994).

The array of sub-linear structural features evident in Figure 1b shows that zones of secondary porosity such as faults are the main controlling factor for the movement of groundwater in the study area. These features are often connected with deep aquifer and serve as channels for upward transport of deep-seated and mixed groundwater to the landsurface (Kerrich, 1986). They also control the spatial variation of groundwater temperature and groundwater salinity.

According to Hamdan and Bahr (1992), four lithofacies characterize the study area: (i) the fluvial Deposits, (ii) sabkha deposits, (iii) desert plain deposits and (v) Aeolian sands.

The water bearing formations of the study area are mainly composed of alluvial deposits in the uppermost part that underlain by clay, gypsum, limestone and marl lithofacies (Murad et al., 2012). Groundwater table in the study area varies from 5.71 to 60.94m below ground level (Hamdan and El-Deeb 1990).

The electrical conductivity of ground water samples collected from groundwater wells of the study area ranges from 2.989 mS/cm in the Neima area (north) to 27.188 mS/cm at Ain Al Fayda (southwest). The total salinity of groundwater varies between 1910 and 17.400 mg/l, with a mean value of 6714 mg/l (Murad et al., 2012). In general, the electrical conductivity, total salinity, groundwater temperature and sodium adsorption ratio increase from eat to west and from north to south (Figure 1b).

3. Material and methods

One of the most important steps was to construct an accurate Digital Elevation Model (DEM). To construct high quality of DEM, we resampled the SRTM DEM (http://srtm.csi.cgiar.org/Index.asp) of ~90m spatial resolution to 30m. The original cell size (0.000834 in decimal degrees) should be 0.000278 and the bilinear interpolation had the higher accuracy and quite effective. Then, the Z-factor of resampled STRM DEM was merged with the Z-factor of 30m spatial resolution ASTER DEM (http://www.gdem.aster.ersdac.or.jp/search.jsp) to generate a more accurate DEM (Samy and Mohamed 2012). Finally, the DEM was enhanced by applying a local moving mean filter to reduce errors in the grid, such as artefacts or blunder errors, random errors or noise and systematic errors (Hengl *et al.* 2003).

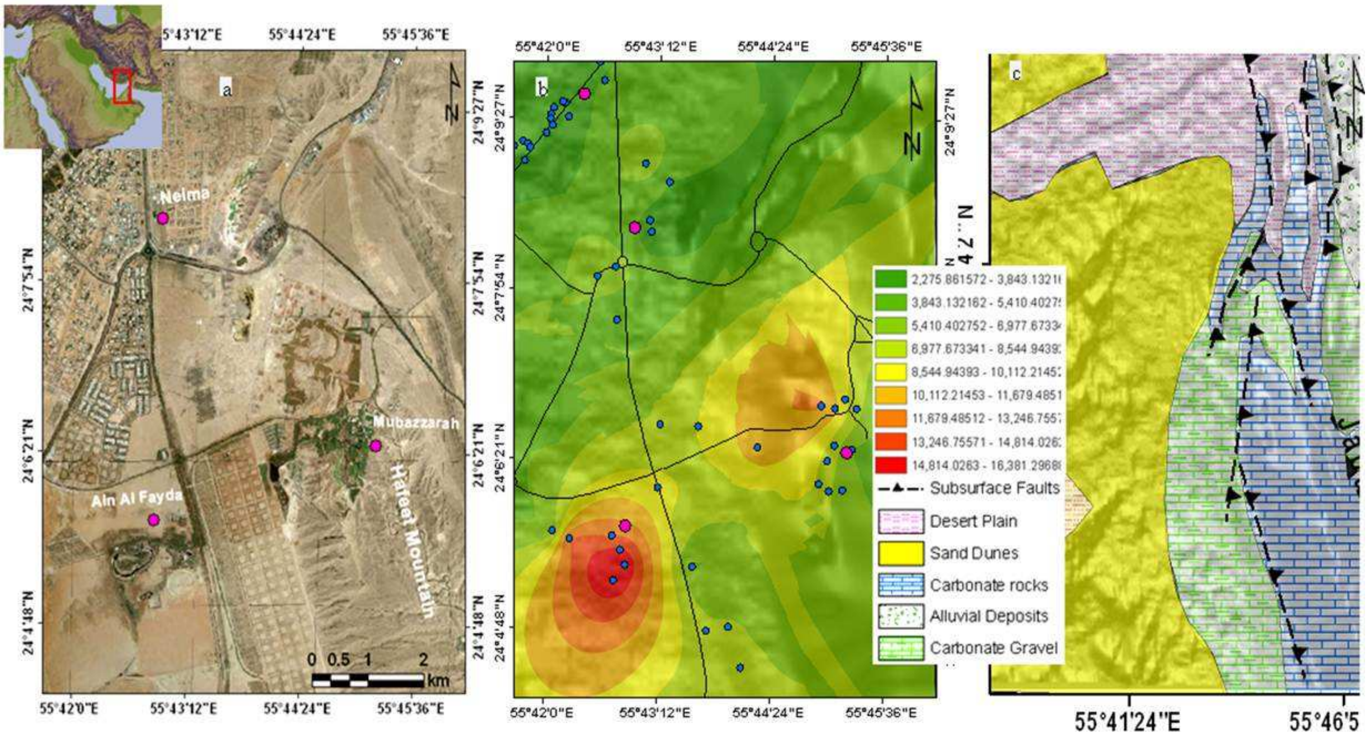

Figure 1. (a) LANDSAT image, (b) Iso-salinity map of groundwater (after Murad et al 2012) and (C) geological map of the study area

3.1 Methods

The indicators of groundwater accumulation and salinity are related to geological fractures, topographic slope, irrigation areas, flow accumulation, aspect and relief of the area. In order to identify and predict groundwater accumulation and groundwater salinity, different thematic maps (factors) were prepared. These include seven different thematic maps as essential factors were integrated in the GIS environment as input layers to perform the groundwater salinity prediction.

The factors include: (i) geological fractures, which serve as channels and hence increase the carbonate rocks dissolution (ii) drainage network, which are often connected with geological structures (Gerasimov and Korzhuev 1979, Ollier 1981), and hence, increases chemical dissolution and karst features development, (iii) relief, which reflect high geological fractures intersections, control flow accumulation and soil salinity, (iv) aspect, which control the flow direction and accumulation, (v) slope, which controls the speed of groundwater, mechanical erosion of carbonate rock and increase and (vi) irrigation area which increases the evapotranspiration and therefore groundwater salinity were considered as crucial factors control groundwater accumulation and groundwater salinity.

Geological fractures were extracted and mapped from enhanced thematic maps of terrain parameters by applying a non linear 3x3 Soble filter with 10% threshold (Abarca 2006, Jordan and Scott 2005, Samy *et al.* 2011b). These maps include slope, aspect and shaded relief in all directions (0°,45°,90°,135°…360°).

The geological fractures were readily mapped because they contrast with the surrounding landscape due to their escarpments (displacements) and/or tone change.

Drainage basins and drainage network were extracted from DEM using D8 algorithm (Jenson and Dominque 1988) that implemented in Arc GIS v.9.2 software. The flow directions were identified automatically using drainage down hill vectors algorithm that implemented in the Ilwise v.3.7 software (ITC 2011). Topographic slope, aspect, relief and curvature were calculated from DEM using ArcGIS v 9.2 software.

The calculated maps were then compared with geological map (Woodward and Al Sharhan 1994) and hydrological data (salinity and electrical conductivity) of samples collected from wells (Murad et al., 2012), together with previous study results, were also used to identify the spatial distribution of groundwater salinity and electrical conductivity in the study area (Khalifa 1997, Al Nuaimi 2003, Murad *et al.* 2010).

4. Results and discussion

4.1 Topographic attributes control flow accumulation

Mapping geological fracture zones in the Hafeet Mountain and its adjacent areas is a proxy for groundwater prospecting in such highly fractured carbonate terrains. The proposed methods using remote sensing data can provide effective means of characterising fracture systems in these areas over large scale. In the southwestern part of Al Ain, the geological fracture trends (Figure 2a) are commonly northwestern-southeastern and north northeast parallel to the fold axis of the Hafeet Mountain (Woodward and Al Sharhan 1994). The faulted blocks are dipping from Zakher and Neima (north) toward Ain Al Fayda (south) and from Mubazzarh (east) toward Neima and Ain Al Fayda (southwest) with difference in elevation of 30m and 100 m respectively (Figure 3). Flow direction, flow accumulation, slope direction, slope gradient, relief and thickness of shallow alluvial aquifer, and hence the level of groundwater are controlled by these two sets of geological fractures (Figure 2). This result is supported by the previous geophysical survey and borehole records (Hunting 1979, Hamdan and Bahr 1992, Garamoon 1996, Murad *et al.* 2010, Murad *et al.* 2012).

The flow accumulation zones, rising of groundwater level and abnormally high discharge of springs are closely associated with highly fractured intensive fracturing controlling upward transport of deep-seated groundwater (Kerrich 1986, Lukin 1987, Florinsky 2000, Murad *et al.* 2012). Geological fractures represent the disclosed zone of the subsurface faulted folding blocks, which is evident from boreholes (Murad *el al.* 2012) and topographic profiles (Figure 3). These features play a vital role in carbonate rock dissolution and increase concentration of anionic and cationic in groundwater as indicated from the dominant and the presence of bicarbonate and sulphate (*Murad et al.* 2012).

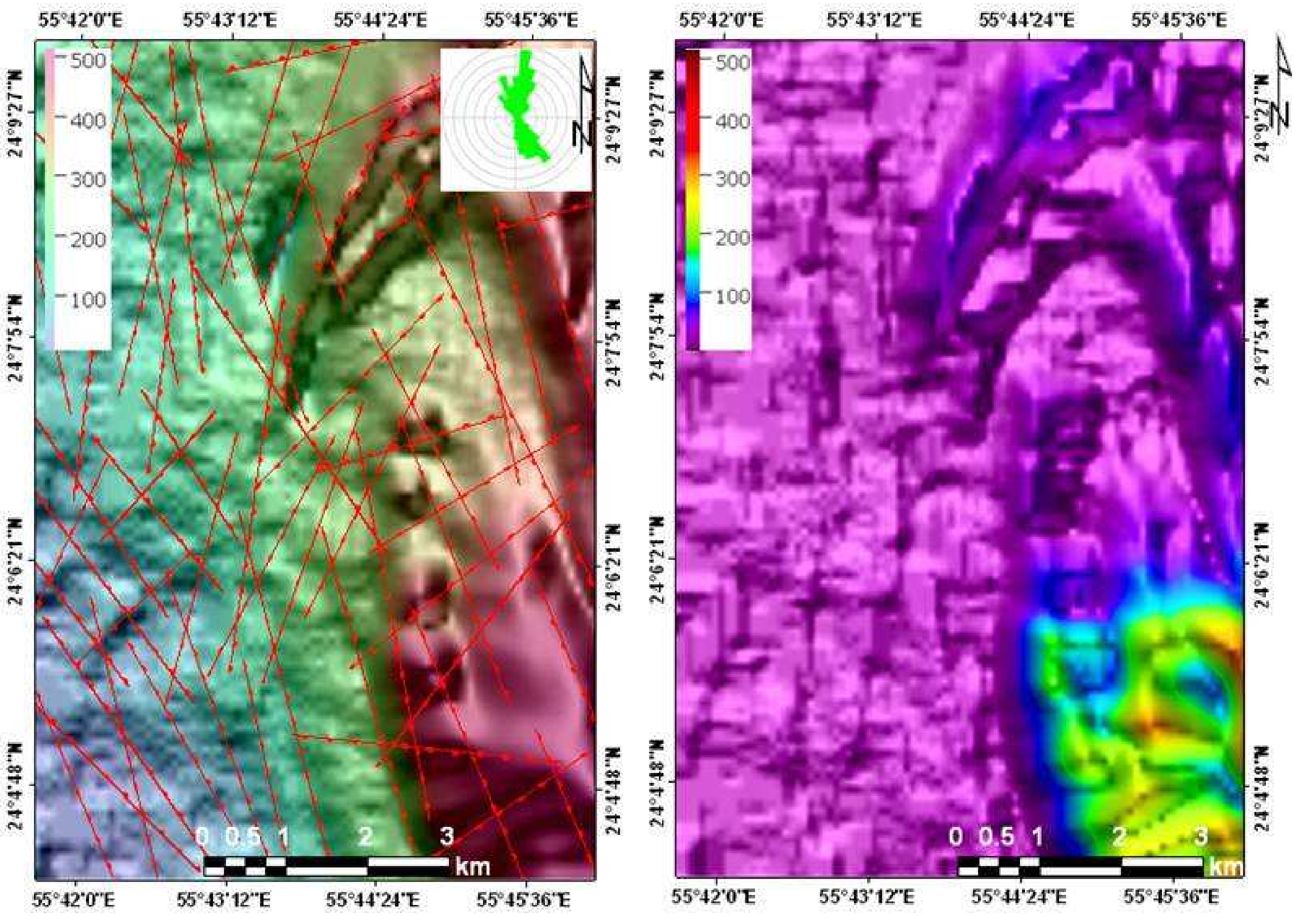

Figure 2. Geological lineaments and (b) topographic relief extracted from DEM. rose diagram highlights the trends of geological lineaments

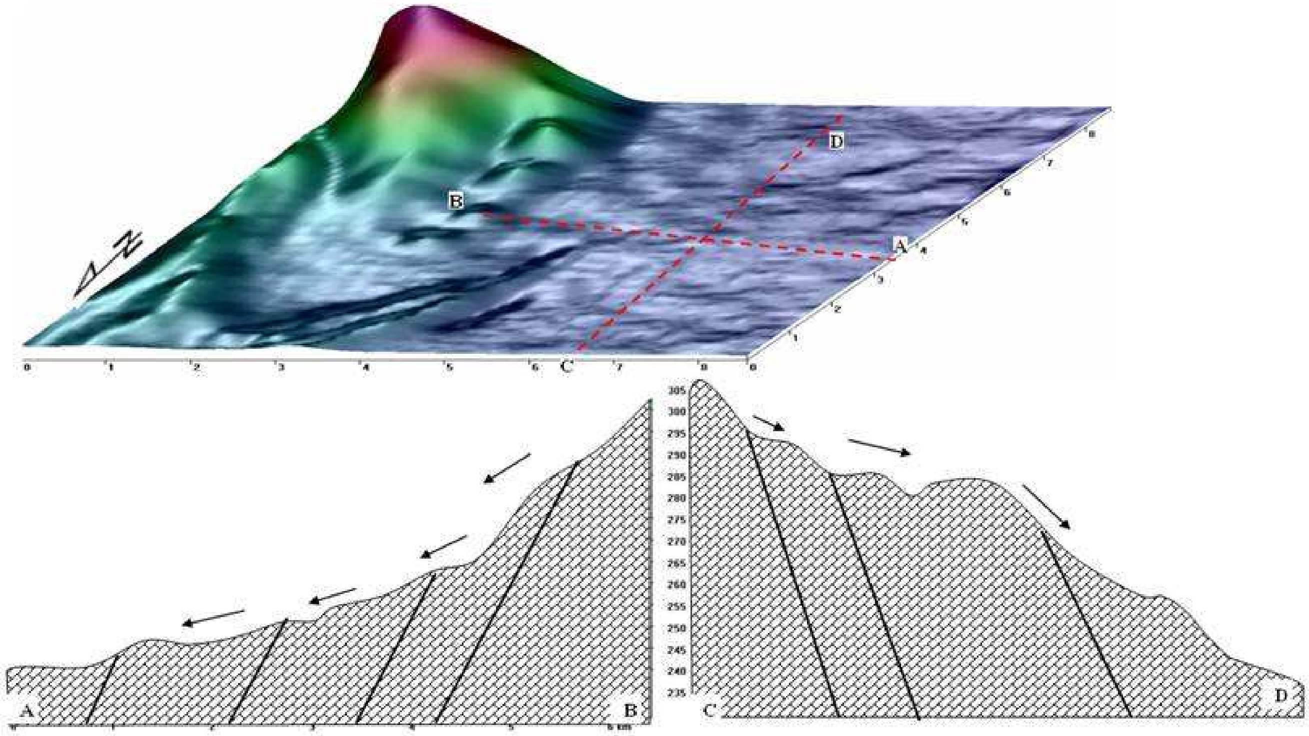

Figure 3. 3D perspective view (up) and N-S and E-W topographic profiles generated from DEM for the study area

In the Mubazzara and Ain Al Fayda, the geological fracture intersections showing low-land like depression in shape with different values for topographic attributes (Figures 4 and 5), controlling flow accumulation and have received most of rainwater and groundwater by gravity (Murad el al., 2012). In Mubazzara area, groundwater recharge occurs mainly in locations of outcropping rock via geological fracture intersections while in Ain Al Fayda there is a lateral flow and upward transport of deep-seated groundwater.

Figure 2b shows very low value (<7m) for topographic relief in Ain Al Fayda (southwest) and Neima area (north) and moderate relief (70m) in Mubazzara area (east). This relief controls surface runoff of water flow over landsurface from the east at Mubazzara to the southwest near Ain Al Fayda and from the north near Neima to the southwest near Ain Al Fayda. The presence of the intensive irrigation areas and springs in Mubazzara and Ain Al Fayda suggests possible lateral and upward transport of deep-seated groundwater to landsurface via geological fractures intersections (Murad *el al.* 2012).

For a slope analysis, topographic slope within Hafeet Mountain was classified as moderate to steep slope (Figure 4a). About 85% of the study was classified as gentle slope (<5°) and signify groundwater decelerate, and hence high rate of infiltration and salt accumulation (Subba 2006). While in Hafeet Mountain there is a higher surface runoff and water is often dissipated. This is in turn will minimize the rate of infiltration.

According to aspect map and aspect distribution by slope rose diagram (Figure 4b), the common slope directions, and therefore flow direction and accumulation are found to be in the SW,WSW and E directions, which is partially depend on fault displacements and intersections (Figure 4b).

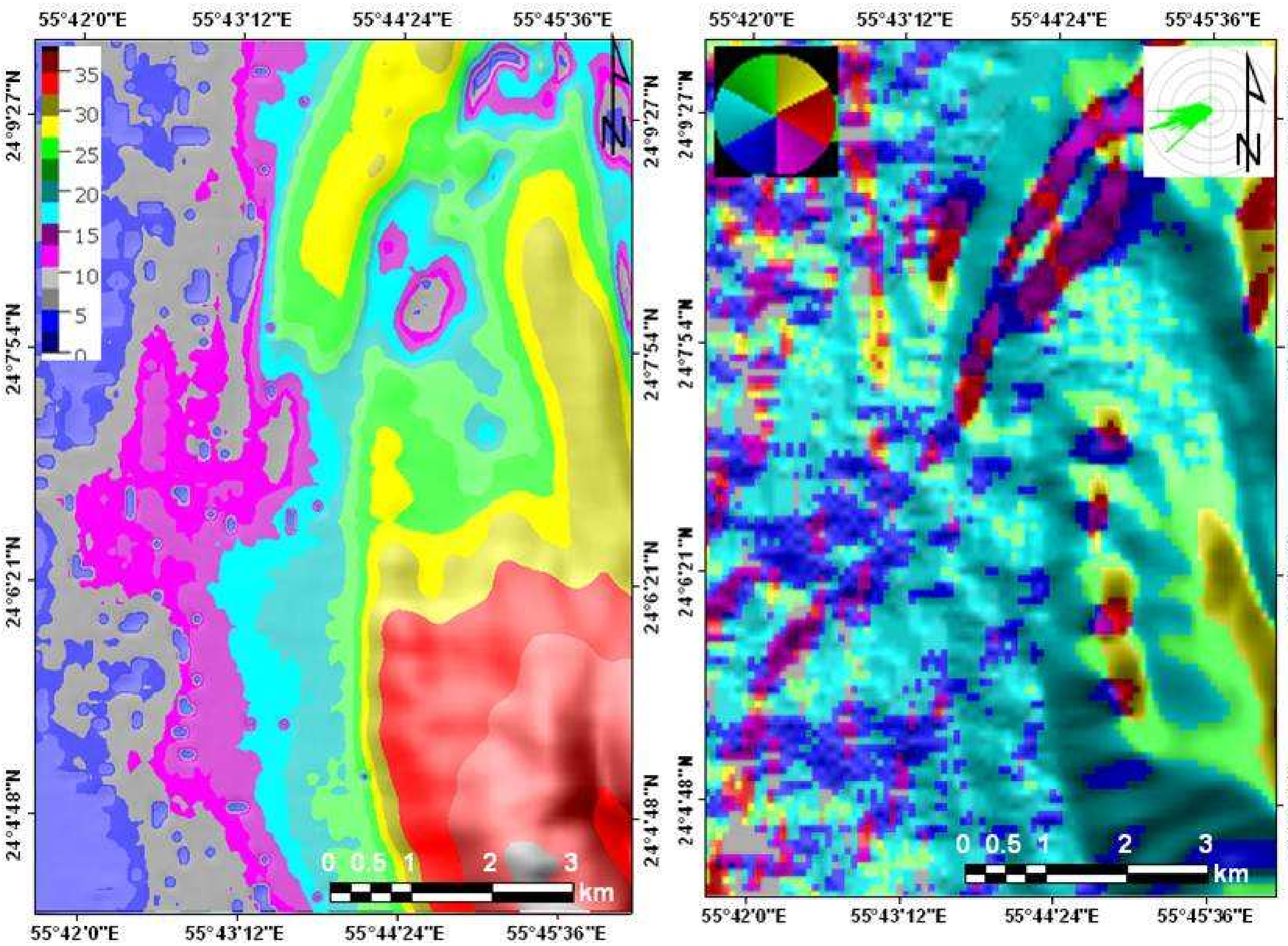

Figure 4. 3D slope map(a) and aspect map (b) calculated from DEM. rose diagram highlights the common slope directions in the study area

Elevation versus average slope graph is shown in figure 5. This diagram shows where generally steep and generally flat areas occur in terms of elevation. For example, as elevation and slope decrease, velocity of water flow, therefore the rainwater received per unite area and its infiltration increase, and therefore groundwater potentiality increase (Zakharov 1940, Florinsky 2000, Subba 2006). This leads to a strong relationship between topographic attributes and geological fractures and groundwater accumulation and groundwater salinity.

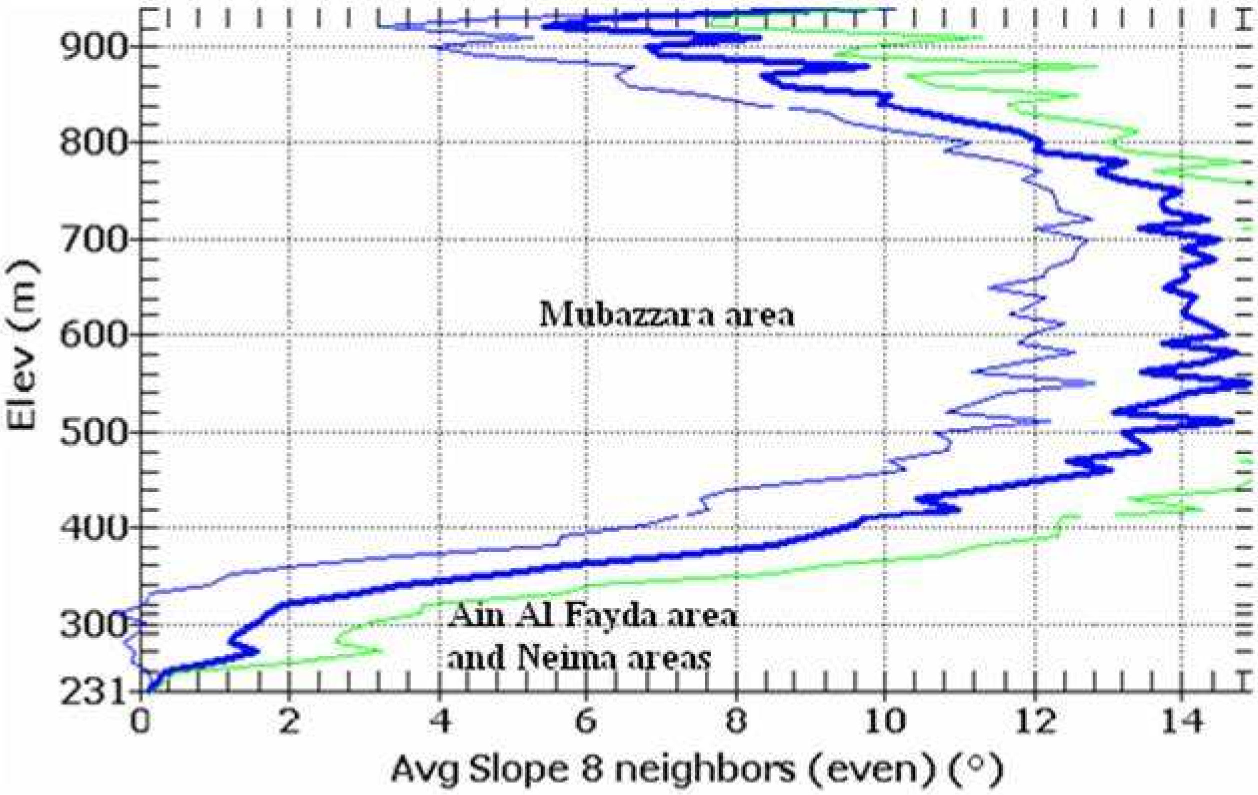

Figure 5. Elevation vs average slope show the positive relationship between elevation and slope, and hence rater precipitation

Drainage downhill, drainage basins and drainage network show where water flow and flow accumulation occur (Figure 6). The maps show that the area is drained by 3 main basins and drainage network emerging from the western limb of Hafeet Mountain at an elevation of >1000m. They drain southwest toward the low-land in Ain Al Fayda and Niema under the influence of geological fracture displacements and slope gradient. They collect rainwater from the largest catchment of total area of 38.15km^2 and 17.77km^2 respectively.

A local flow from the western limb of Hafeet Mountain toward Ain Al Fayda, Neima and sand dunes has developed in the alluvial shallow aquifer that overlie highly fractured carbonate rocks (Jeffrey et al., 2007). Since flow accumulation has higher correlation with catchment area and slope gradient (Moore *et al.* 1993), relative deceleration is the mechanism controlling groundwater potential (Florinsky *el al.* 2000). As catchment area increases and slope gradient decreases, soil moisture and flow accumulation increases. Catchment area and slope can play a considerable role in the control of groundwater recharge and redistribution of water salinity (Speight 1980, Florinsky 2000).

4.2 Correlation analysis between topographic attribute and groundwater salinity

The strong spatial variability in groundwater salinity and topographic attributes and irrigation area associations was easily observable when we analysed them at each point and sites in the study area (Figures 1b,6 and Tables 1). The spatial correlation and analysis showed that groundwater salinity were dependent on the chemical composition of host rocks, the distance between upstream and down stream (flow length), slope gradient, aspect and topographic relief. These results were supported by the previous hydrogeochemical analysis of samples collected from groundwater wells (Murad *et al.* 2012) (Figures 1b,6 and Tables 1).

The host rock determines the type of cations and anions in groundwater. For example, groundwater with high concentration of Mg^{2+}, Ca^{2+}, $SO4^{2-}$ and $HCO3^{2-}$ reflects anions and cations resulting from dissolution of limestone, dolomite and gypsum, while groundwater with high concentration of Cl^-, Na^+ and NO_3 reflects rock salt and intensive irrigation and agricultural areas. Groundwater with high concentration of K^+ reflects cation resulting from dissolution of igneous rock (Mathess 1982, Khalifa 1997, Murad *et al.* 2012).

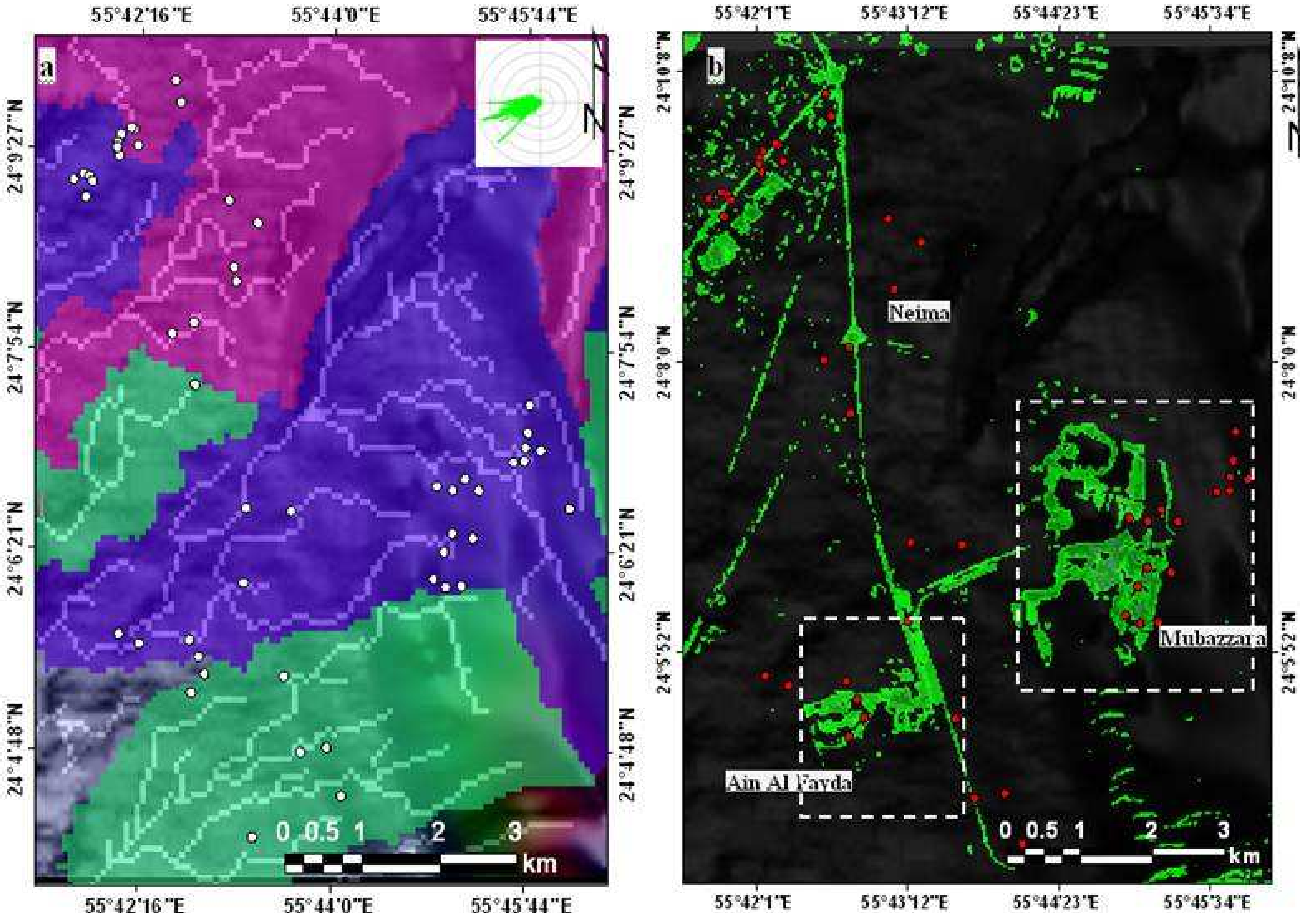

Figure 6. (a) Drainage basins and drainage network map and (b) NDVI map for the study area. These are draped over DEM

The long distance between upstream and downstream can lead to salinization of the aquifer and groundwater by leaching process in the downstream (Himida 1966, Murad *et al.* 2012). This leads to a symmetrical relationship between stream length and the groundwater salinization. Groundwater of Ain Al Fayda area is expected to have higher concentration of cations and anions than groundwater of Mubazarha.

The low slope, low topography and low relief can lead to decrease water flow. In turn, the flow decreasing can lead to salinization of the aquifer of the groundwater and groundwater (Tkachuk 1970). So, groundwater salinity of Ain Al Fayda is much higher than groundwater of Mubazzar and Neima (Table 1 and Figures 6,7). This is a normal result substantiating facts that flow accumulation zones and hence groundwater salinization often related to fault intersections (Poletaev 1992, Florinsky 1993, Florinsky 2000).

Spatial correlation also showed that groundwater salinity is dependent on flow direction and intensity of irrigation areas, and therefore evpotranspiration. As the irrigation area increases, the evapotranspiration and groundwater salinity increase (Figures 1b, 6b). In Mubazzar and Ain Al Fayda areas, which have the highest percentage of irrigation and agricultural areas (Figure 7), groundwater is expected to have high concentration of chloride, bromine and sodium (Murad *et al.* 2012). Groundwater of Ain Al Fayda showed high salinity comparing with Mubazara area.

This is because Ain Al Fayda area is located on terrain with low relief, low slope% and low topography, and hence receives lateral and upward transport of deep-seated and mixed groundwater via fractured zones. Generally, the concentration of anions and cations in groundwater increase from east to southwest and from north to south (HydroConsult 1987, Khalifa 1997, Khalifa, 2003, Murad *et al.* 2012). Thus, groundwater of Ain Al Fayda area has the highest concentration of cations (e.g Na^+, Ca^{2+}, Mg^{2+} and K^+) and anions (e.g. Cl^-, $SO4^{2-}$and $HCO3^{2-}$) in the study area.

The results also showed strong correlation between physical properties such as groundwater temperature, electrical conductivity (Murad *et al.* 2012) and topographic attributes and geological fracture intersections.

The high temperature of collected groundwater samples (Murad *et al.* 2012) showed an increase from Ain Al Fayda (west) toward Mubazzar (east). This is because Mubazzara area was found to be located on deeply-highly fractured rocks, which can serve as passways for upward transport of deep-seated groundwater to the land surface (Kerrich 1986).

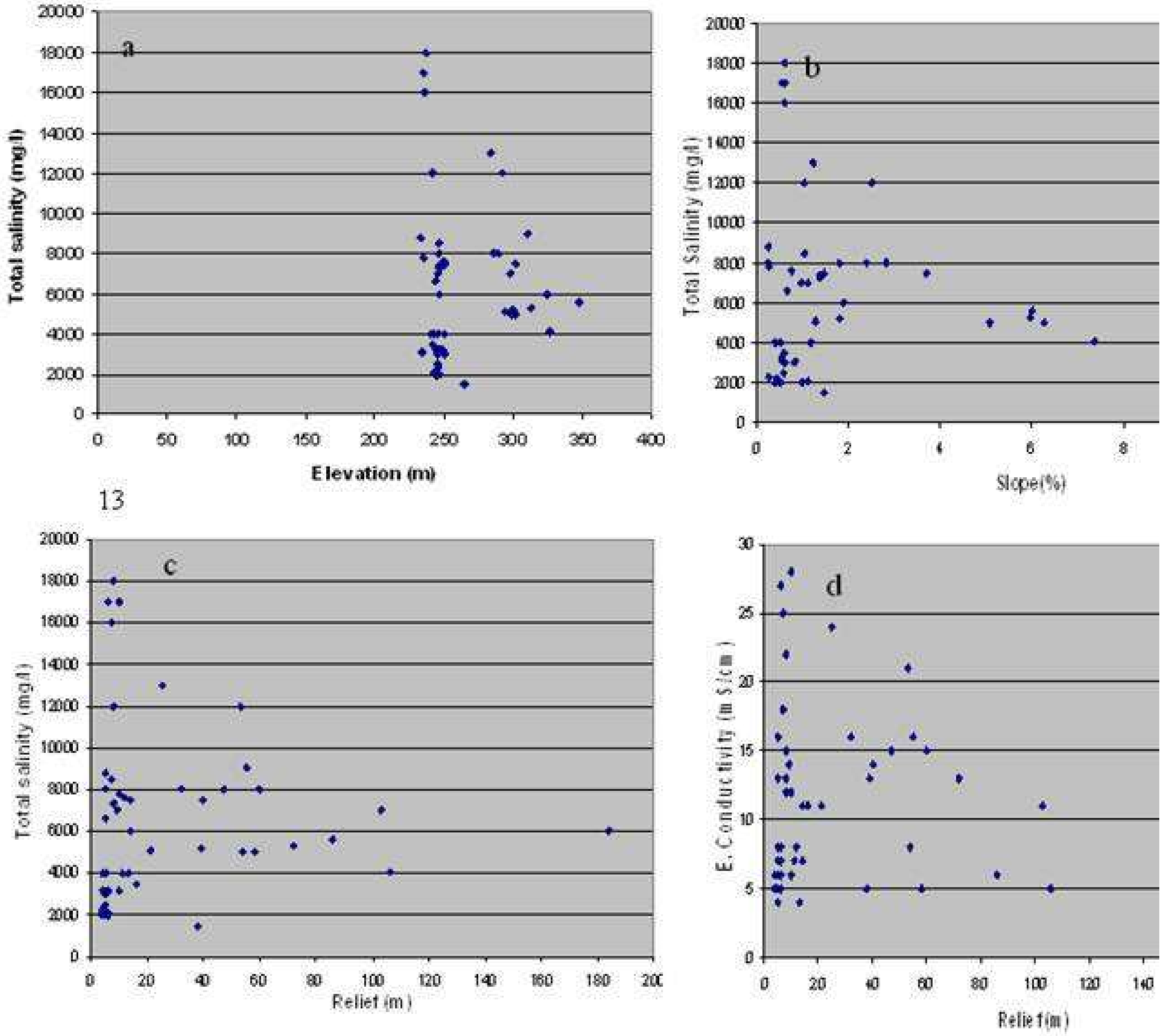

Figure 7. Graphs showing the spatial correlation between terrain parameters (elevation, slope and relief) and total salinity and electrical conductivity of groundwater samples collected from wells

The spatial correlation between geological lineament displacements and intersections and topographic attributes can provide better understanding of spatial distribution of the groundwater salinity and groundwater accumulation (Burt and Butcher 1985, Florinsky 2000). This is because these topographic attributes take into consideration both a local slope gradient and slope direction (Gessler *et al.* 1995). The verification results showed that the application of remote sensing and topographic attributes to predict and identify the spatial distribution of the groundwater accumulation and groundwater salinity was cost and effective than traditional method using geophysical survey and field investigation , especially in arid and desert regions.

These results can be used as basic hydrological information to assist hydrological setting and land use management. The method to be more generally applied, a more geophysical and ground survey are needed.

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Table 1. Topographic attributes at each groundwater well and corresponding hydrological data collected from groundwater samples

Topographic attributes at each groundwater well						Hydrological analysis of each groundwater sample [2]		
N	E	Elev.(m)	Slope (%)	Aspect	Relief (m)	EC	Isosalinity	SAR
24.15627	55.69863	245	0.43	294.8	4	5	2200	5
24.10611	55.75008	286.09	1.81	360	60	15	8000	19
24.10112	55.75029	298.35	0.98	90	103	11	7000	18
24.10071	55.75348	324.44	11.25	278.3	184	12	6000	16
24.10228	55.74836	310.4	11.03	69.9	55	16	9000	20
24.10816	55.7499	286.39	2.83	255.2	47	15	8000	19
24.16312	55.71134	250	0.41	208.4	4	6	4000	12
24.16676	55.70859	250.15	0.8	257	5	7	3000	5
24.16012	55.70387	246.46	0.58	199.8	5	5	3100	6
24.16187	55.70241	247.56	0.54	180	4	6	3200	5
24.1569	55.70406	246			5	8	4000	6
24.15921	55.69988	245.55	0.61	287.1	5	5	3000	6
24.15833	55.69957	245.55	0.59	270	5	7	2500	7
24.15424	55.70121	245.19	0.41	208.4	4	6	2000	6
24.15643	55.70103	246.02	0.27	227.2	4	5	2300	8
24.1117	55.7521	292.38	2.52	315.8	53	21	12000	26
24.11625	55.75349	289.55	2.41	283	32	16	8000	18
24.11416	55.7484	284.03	1.23	331.6	25	24	13000	30
24.10601	55.75615	326.9	7.36	287.1	106	5	4100	16
24.1135	55.75719	301.69	3.7	331.6	40	14	7500	19
24.11821	55.75922	294.58	1.29	294.8	21	11	5100	11
24.1175	55.7629	299.76	1.8	300	39	13	5200	10
24.11899	55.7656	313.03	5.96	280.5	72	13	5300	8
24.12132	55.76334	299.39	5.09	265.9	54	8	5000	13
24.10993	55.76936	347.43	6	289.3	86	6	5600	5
24.1244	55.76347	301.56	6.27	275	58	5	5000	15
24.15521	55.69545	244.21	0.67	324.2	5	6	6600	9
24.15346	5.695627	245.25	0.53	312.8	5	4	2000	6
24.15214	55.69644	245.96	0.27	132.8	4	5	2300	5
24.15402	55.69354	243.32	1.12	299	6	6	2100	6
24.15082	55.69613	244.38	0.54	180	6	5	3200	7
24.10073	55.72011	241.35	1.19	261.2	13	4	4000	4
24.09459	55.70469	233	0.27	132.8	5	16	8800	16
24.06922	55.72202	235.39	0.61	252.9	6	27	17000	21
24.08673	55.71243	235	0.27	227.2	10	12	7800	22
24.08704	55.71338	235	0.54	180	10	28	17000	19
24.09218	55.71509	237.24	0.61	252.9	8	22	18000	22
24.09289	55.71205	236.63	0.61	287.1	7	25	16000	16
24.13392	55.70924	241.77	1.04	249.7	8	15	12000	15
24.07387	55.73522	246.7	1.9	247.7	14	11	6000	43
24.07988	55.73453	250.13	1.47	248.4	14	7	7500	14
24.10959	55.72769	250	0.75	195.1	12	8	7600	13
24.13323	55.71388	246.26	1.04	290.3	7	18	8500	25
24.12692	55.71314	246.34	1.38	262.5	8	13	7300	13
24.09052	55.72644	243	0.53	227.2	11	7	4000	17
24.07954	55.72942	242.17	0.59	270	16	11	3500	17
24.11203	55.72112	245.86	1.12	241	9	14	7000	15
24.15232	55.71768	247.05	1.38	238.4	8	12	7400	16
24.14061	55.71956	247	0.27	227.2	5	13	8000	17

24.14309	55.71873	247.19	0.99	259.5	6	7	2000	5
24.14868	55.72091	249.56	0.54	180	10	6	3200	10
24.0953	55.7018	233.83	0.86	245.2	6	8	3100	11
24.10748	55.73841	264.45	1.47	291.6	38	5	1500	6

5. Conclusion

Using remote sensing and GIS and spatial correlation, it was possible to identify and predict groundwater sites of groundwater potential and groundwater salinity in the study area. The results showed that the area is drained by 3 main basins emerging from Hafeet Mountain and drain southwesterly toward Ain Al Fayda and sand dunes. The results also showed all topographic attributes and hydrological elements are strongly structural controlled by NW and NNE trending fault zones. They collect rainwater from the largest catchment of total area of 38.15km^2 and 17.77km^2 respectively.

The spatial correlation has demonstrated that the groundwater accumulation and groundwater salinity are strongly controlled flow direction, slope%, aspect, relief catchment area, distance between upstream and down streams, chemical composition of host rock and intensity of irrigation areas. Sites, which have classified as low topography, low relief and low slope% and are located on highly fractured carbonate rocks, correlate well with those sites of high groundwater potential and groundwater salinity as indicated by intensity of irrigation area and groundwater samples collected from groundwater wells.

These findings prove the usefulness of the proposed methods in predicting and identifying sites of high groundwater accumulation and groundwater salinity. Furthermore, the study showed that, the groundwater discharges from Hafeet Mountain into southwest ward in Mubazzara, Neima and Ain Al Fayda areas.

Similarly, groundwater salinity increases from Hafeet Mountain southwest ward in Mubazzara, Neima and Ain Al Fayda areas. Results, therefore, demonstrate that an integration of remote sensing and GIS can be used in predicting and identifying sites of groundwater accumulation and groundwater salinity in arid regions.

References

Abarca, M.A. (2006), Lineaments extraction from digital terrain models case study san Antonio del Sur area, South - Eastern area, MSc. Thesis, the international institute of geoinformation and earth observation.

Al Nuaimi H. S. (2003), Hydrogeological and Geophysical Studies on Al Jaww plain, Al Ain Area, United Arab Emirates," M.Sc Thesis, United Arab Emirates University, Al Ain, 2003, 159 p.

Burt, T.P., Butcher, D.P. (1985), Topographic controls of soil moisture distribution. *Journal of Soil Science* 36 (3), 469–486.

Finzi, V. (1973), Late Quaternary Subsidence in the Musandam Expedition, 1971-1972, Scientific Results, Part I, Geograph. J. 139, pp. 414-421.

Florinsky, I.V. (2000), Relationships between topographically expressed zones of flow accumulation and sites of fault intersection: analysis by means of digital terrain modelling. *Environmental Modelling and Software* 15 (1), 87–100.

Florinsky I.V., Eilers R.G., Manning G.R., Fuller L.G. (2002), Prediction of soil properties by digital terrain modeling *Environmental Modelling & Software* 17 (2002) 295–311

Garamoon, H.K. (1996), "Hydrogeological and Geomorphologi-cal Studies on the Abu Dhabi-Dubai-Al Ain Triangle, UAE," Unpublished Ph.D. thesis, Geology Department, Faculty of Sciences, Ain Shames University, Egypt, 1996, 127 p.

Gessler, P.E., Moore, I.D., McKenzie, N.J., Ryan, P.J. (1995), Soillandscape modelling and spatial prediction of soil attributes. *International Journal of Geographical Information Systems* 9 (4), 421–432.

Glennie, K.W., Boeuf, M.G., Hughes, M.W., Clarke, M., Moody-Stuart, W.F., Pilaar, Reinhardt, B.M. (1974), Geology of the Oman Mountains, Verhandelingen van het oninklijk Nederlands geologisch mijnbouwkundig Genootschap. *The Royal Dutch Geological and Mining Society (KNGMG)*, Parts 1 and 2, , p. 423.

Hamdan A. A. and El-Deeb, W. Z. (1990),"Stratigraphy of the Paleogene Succession of Jabal Malaqet, West of the Northern Oman Mountains.," Fac. Sci., UAE University., Vol. 2, 1990, pp. 30-39.

Hamdan A.A. and Bahr, S.A. (1992), Lithostratigraphy of the Paleogene Succession of Northern Jabal Hafit., Al-Ain Area, UAE., M.E.R.C., Ain Shams University, Earth Sci. Ser., Vol. 6, 1992, pp. 201-224.

Hengl, T., David, G., Rossiter, F. (2003), Supervised Landform Classification To Enhance and Replace Photo-Interpretation in Semi-Detailed Soil Survey Soil Sci. Soc. Am. J. 67:1810–1822 (2003). *Soil Science Society of America* 677 S. Segoe Rd., Madison, WI 53711 USA.

Himida, I.H. (1966), Artesian water of the Nubian sandstones in the oases of the Libyan Desert, U.A.R. (in Russian). *Geological Series* No. 6, MGRI, Moscow, pp 91–103

Hunting, Report on a mineral survey of the U. A. E. (1977-1979), Ministry of Petroleum and Mineral Resources, Vol.1, (1979), pp. 1-34.

HydroConsult, (1987), Reconnaissance Report and Development Proposals, Abu Dhabi, (UAE) Eastern Region Water Re-sources," *Ministry of Petroleum and Mineral Resources Report*, Government of Abu Dhabi, 1987, 126 p.

Jordan, G., and Schott, B. (2005), Application of wavelet analysis to the study of spatial pattern of morphotectonic lineaments in digital terrain models. A case study. *Remote Sensing of Environment* 94 (2005) 31–38.

ILWIS Academic 3.5 (2009), International Institute for Geo-information Science and Earth Observation. P.O.Box 6,7500 AA-Enschede, the Netherlands.

Jaiswal, R.K., Mukherjee, S., Krishnamurthy, J., Saxena, R. (2003), Role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development-an approach. *International Journal of Remote Sensing,* 24:993–1008

Jeffrey L.I., and Warren W.W. (2007), Solute and isotope constraint of groundwater recharge simulation in an arid environment, Abu Dhabi Emirate, United Arab Emirates. *Hydrogeology Journal* (2007) 15: 1307–1315

Jenson, S.K., and Domingue, J.O. (1988), Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis. *Photogrammetric Engineering and Remote Sensing*,Vol. 54, No. 11, November 1988, pp. 1593–1600.

JICA, (Japanese International Cooperation Agency) (1996), The master plan study on the groundwater resources development for agriculture in the vicinity of Al Dhaid in the UAE, JICA *International Cooperation Agency*, (1996), Final Report.

Kerrich, R. (1986), Fluid transport in lineaments. Philosophical Transactions of the Royal Society of London, A. *Mathematical and Physical Sciences* 317, 219–251.

Khalifa, M. A. (1997), Hydrogeology of the Geothermal Frac-tured Rock Well Field at Jabal Hafit, Abu Dhabi Emir-ate, *Proceedings of the* 3rd *Gulf Water Confer*, Muscat, 1997, pp. 125-140

Khalifa, M. A. (2003), Geohydrology and the Source of Flowing Well Water in Al-Neima Area, Al Ain, Abu Dhabi Emirate, UAE," National Drilling Company and United States Geological Survey, 2003, 9 p.

Krishnamurthy, J.N., Venkatesa, K., Jayaraman, V., Manivel, M. (1996), An approach to demarcate ground water potential zones through remote sensing and geographical information system. *Int J Remote Sens* 17:1867–1884

Lukin, A.A. (1987), Experience in Development of Morphostructural and Hydrological Analysis Technique. Nauka, Novosibirsk 111 pp., in Russian.

Mathess, G. (1982), The Properties of Groundwater" John Wiley and Sons, New York, 1982, pp. 215-255.

Menges, C.M., Hadley, D.G., Woodward, D.G., Mohamed, F.A. (1993), Geology and geophysics, groundwater resources of Al-Ain area, Abu Dhabi Emirate. In: *US Geological Survey Administration Rep* 93-001, pp 74–167

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A. (1993), Soil attribute prediction using terrain analysis. *Soil Science Society of America Journal* 57 (2), 443–452.

Murad A.A., Al Nuaimi H., Al Hammadi M. (2007), Comprehensive Assessment of Water Resources in the United Arab Emirates (UAE) *Water Resour Manage* (2007) 21:1449–1463 DOI 10.1007/s11269-006-9093-4

Murad, A., Baker, H., Mahmoud, S., Gabr, A. (2010), Groundwater Level Prediction at a Pilot Area in Southeastern Part of the UAE using Shallow Seismic Method

Murad A., Mahgoub F., Hussein S. (2012), Hydrogeochemical Variations of Groundwater of the Northern Jabal Hafit in Eastern Part of Abu Dhabi Emirate, United Arab Emirates (UAE). International *Journal of Geosciences*, 2012, 3, 410-429 doi:10.4236/ijg.2012.32046 Published Online May 2012

Murthy, K.S. (2000), Groundwater potential in a semi-arid region of Andhra Pradesh: a geographical information system approach. *Int J Remote Sens* 21(9):1867–1884

Obi, R.P., Chandra, M.K, Srivastav SK, Srinivas CV, Maji, A.K (2000), Evaluation of groundwater potential zones using remote sensing data- a case study of Gaimukh watershed, Bhandara di

Pratap K, Ravindran KV, Prabakaran, B. (2000), Groundwater prospect zoning using remote sensing and geographical information system: a case study in Dala-Renukoot Area, Sonbhadra District Uttar Pradesh. *J Indian Soc Remote Sens* 28(4):249–263

Prasad, R.K., Mondal, N.C., Pallavi, Banerjee, N.M., Singh, V.S. (2007), Deciphering potential groundwater zone in hard rock through the application of GIS. *Environmental Geology* DOI 10.1007/s00254-007-0992-3

Rathorea, V.S., Nathawata, M.S., Champati, R.P.K. (2008), Influence of neotectonic activity on groundwater salinity and playa development in the Mendha river catchment, western India. International Journal of Remote Sensing Vol. 29, No. 13, 10 July 2008, 3975–3986

Samy, I., Shattri, M., Bujang, B.K., Ahmad, R.M., (2011b), Structural geology control the limestone bedrock that associated with piling problems using remote sensing and GIS: a modified geomorphology method. *Environ Earth Sci.* DOI 10.1007/s12665-011-1440-y

Samy, I.E. and Mohamed M.M. (2012), Natural hazards susceptibility mapping in the Kuala Lumpur, Malaysia: an assessment using remote sensing and geographic infprmation system (GIS). *Geomatics, Natural hazards and risk.,* 2012, 1–21, iFirst article

Singh, A.K., Prakash, S.R. (2002), An integrated approach of remote sensing, geophysics and GIS to evaluation of groundwater potentiality of Ojhala sub watershed, Mirzapur District, U.P. India (http://www.GISdevelopment.net)

Speight, J.G. (1980), The role of topography in controlling throughflow generation: a discussion. *Earth Surface Processes* 5 (2), 187–191

Srinivasa, R.Y., Jugran, K.D. (2003), Delineation of groundwater potential zones and zones of groundwater quality suitable for domestic purposes using remote sensing and GIS. *Hydrogeol Science Journ*al 48:821–833

Subba R.N. (2006), Groundwater potential index in a crystalline terrain using remote sensing data. Environ Geol (2006) 50: 1067–1076 DOI 10.1007/s00254-006-0280-7

Tkachuk, V.G. (Ed.), 1970. Hydrogeology of the USSR, vol. 8. The Crimea. Nedra, Moscow 364 pp., in Russian.

Todd, D.K. (1980), Groundwater hydrology, 2nd edn. Wiley, New York, p 535

Woodward, G.L. and Al Sharhan, A.S. (1994) Domlomitization and Chertification of the early Eocene Rus Formation in Abu Dhabi, UAE Sedimentary Geology, (91), p. 273-285.

Zakharov, S.A. (1940), Importance of slope aspect and gradient for soil and vegetation distribution in the Great Caucasus. *Journal Botanique de l'URSS* 25 (4–5), 378–405 (in Russian).