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Hydrogeochemical Attributes and GIS Spatial Modeling in Determining Areas for Horizontal Expansion of Development Projects in East Uweinat, Egypt

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Abstract: East Uweinat is an important reclaimed area at the southern part of Western Desert of Egypt. The Nubian Sandstone Aquifer System (NSAS) is the sole water source used for all purposes for the last three decades. Determining the priority areas available for horizontal expansion of development projects, depending on the hydrogeological characteristics of the NSAS, has become an essential task. The potentiometric maps of 1990s and 2008 indicated balanced levels in 1980 and 1990s, followed by an accelerated decline from 1990s to 2008. The selected hydrogeochemical attributes represented by the depth to water, aquifer saturated thickness, total dissolved solids and sodium adsorption ratio were integrated to perform a binary-weighted spatial suitability modeling (BSSM-WSSM) techniques to determine the priority areas for development and areas suitable for further horizontal expansion. The BSSM model pinpointed to a minor 1st priority area (1,041 km^2) that occurs mostly in the intensively developed area which are characterized by groundwater heavy consumption and a major 2nd priority area (19,381 km^2) which refers to a lower quality of the aquifer in terms of the given prioritization criteria. The WSSM identified three more priority classes subdivided from the 2nd priority class, namely, the 2nd (7,793 km^2), 3rd (9,976 km^2) and 4th (1,622 km^2) priority subclasses. These priority subclasses represent the possible areas for development that are located to the N-S-SW parts of the study area. The distribution of aquifer transmissivity (T) and hydraulic conductivity (K) values gave high credibility to the results of the BSSM-WSSM model results.

Key words: Egypt, western desert, Nubian sandstone aquifer system, geographic information system, binary-weighted suitability spatial modeling

INTRODUCTION

East Uweinat area is an important area of agricultural reclamation in the southwestern part of the Western Desert of Egypt, which attracted enormous investments of governmental and private sectors in the last three decades. The Nubian Sandstone aquifer system (NSAS) is the sole water resource used for all development purposes. The land and groundwater resources of this area cover the requirements needed for the reclamation and implementation of new communities (GPC, 1984; GARPAD, 1994). The regional study area of East Uweinat is located between latitudes 22° 00' 24.68"-23° 27' 35.53" N and longitudes 27° 59' 50.62" -29° 13' 36.72" E, with an area of about 20, 438 km^2 (Fig. 1, 2).

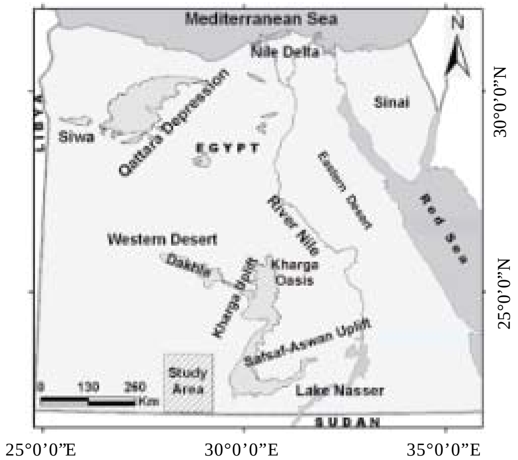


Fig. 1: Location map of the study area

The area of study is generally a flat plain with hill ridges and scarps, which are mostly rugged and rough. The ground surface elevation varies from about 225-420 m above sea level (masl) (Fig. 3). It is characterized by high temperature and low relative humidity during summer. It has also has a long dry rainless summer and short rainless winter. Wind velocity increases sometimes causing sandstorms, especially during the Khamasine periods. The daily mean temperature is 22.86°C. It varies between 12.8°C in January

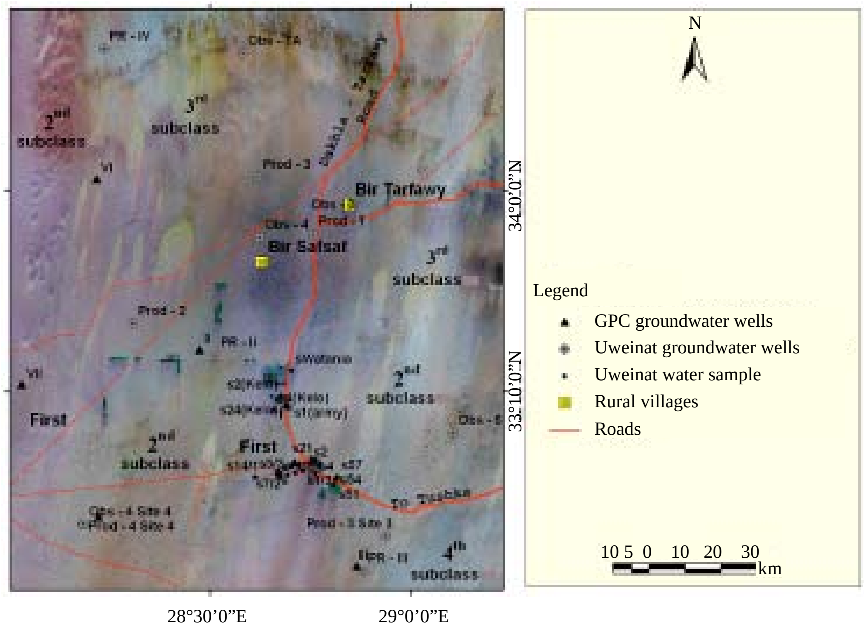


Fig. 2: ETM+satellite image (bands 7 4 2) of the study area (acquired in 2002)

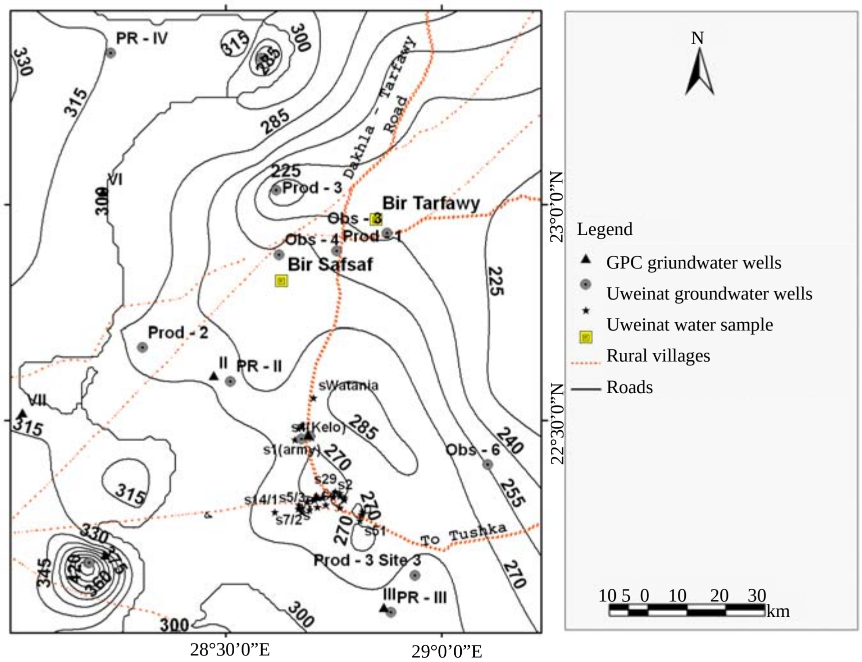


Fig. 3: Location of groundwater wells, east Uweinat area

to 30.7°C in July. The average maximum temperature is 30.7°C. It varies between 17.1°C in January to 39.95°C in June, while the highest recorded temperature was 46.0°C. The average annual minimum temperature is 14.5°C. It

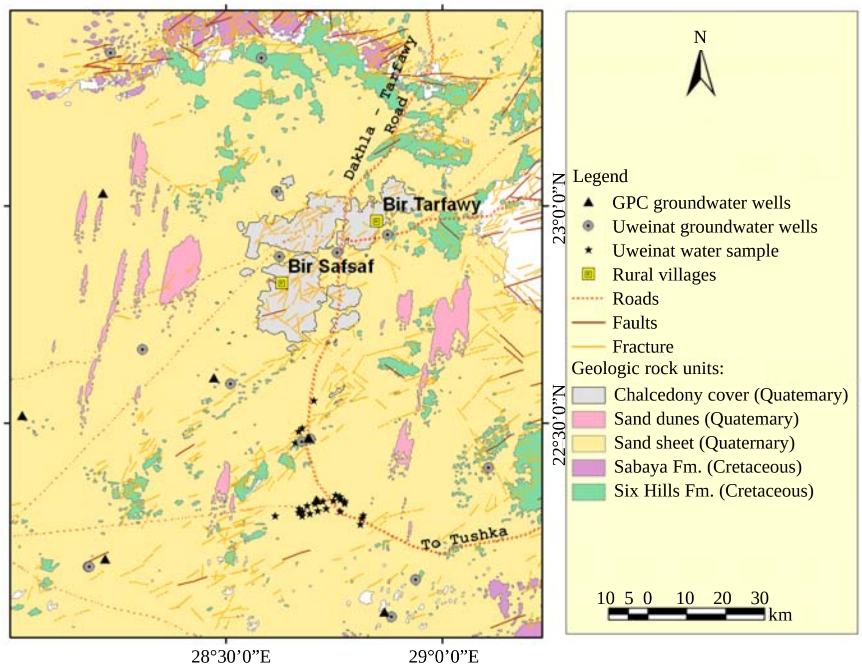


Fig. 4: Geologic map of east Uweinat area (CONOCO, 1987 NG36SW-Luxor sheet)

varies between 5.2°C in December to 22.1°C in July. The annual average relative humidity is 28.8%. It reaches the highest values in January (42.8%) and the lowest values are during May (18.5%).

Geologically, the dominant rock units occupying this area extend from Cretaceous to Quaternary (Fig. 4). Meanwhile, the Nubian Sandstone (Six Hills Formation) is considered as the main exploitable water-bearing formation. This aquifer system is used for the agricultural and socio-economical development of the Western Desert of Egypt. The Nubian Sandstone Aquifer System (NSAS) was formed by the local infiltration during the past wet periods (pluvial periods), which ended in the Northeastern Sahara at about 8000 years ago, while ended in the south (Nubian Desert; northeast of Sudan) at about 4000 years ago (Heinl and Thorweihe, 1993). Sedimentary units of the East Uweinat and southern areas of the Western Desert have been extensively studied for their freshwater potential, among them (GPC, 1984; Nour, 1996; Heinl and Thorweihe, 1993; Robinson *et al.*, 2007; Elewa *et al.*, 2010; Nahry *et al.*, 2010). The oldest exposed rocks in the studied area are the crystalline basement rocks of Precambrian age. Overlying basement rocks, there are different rock units with different ages, with well-authenticated unconformable relationships (GSE, 1987) (Fig. 4). The tectonic movements, which affected the area, probably, started early in the Precambrian. They sculptured the southern part of Egypt into three major intracratonic basins and relatively small and shallow basins. These basins occupy now the Nubian Plateau, Dakhla and Barket El-Shab areas and they have in between the Nakhlai-Aswan High and Tarfawi Kharga High. Two main sets of faults were noticed, a north-south set observed in the vicinity and an E-W set, which crosses the area for a long distance. Supplementary sets of northeast and northwest trends are also noticed. It is possible that these faults are associated with the uplift of the basement in this area. At the study area, a thick subsurface section of Nubian formations exists. This section was investigated by different authorities, such as the General Petroleum Company (GPC, 1984) and the General Authority for Rehabilitation Projects and Agricultural Development (GARPAD, 1994). The maximum fully penetrated thickness of this section reaches 723 m in Well No. 27 (GARPAD, 1994). It is assigned to Pre-Cenomanian.

From 1980s to 2010s, exploration and exploitation drilling campaigns along the southern part of the Western Desert of Egypt were conducted to assess the water resources of the NSAS (GPC, 1984; GARPAD, 1994; Nour, 1996; Elewa *et al.*, 2010) (Fig. 3). The transboundary NSAS covers an area of about 2.4 million km^2 and extends in south Libya, Egypt, north Sudan and northeast Chad (Thorweihe, 1990) and also extends as far north as to

Sinai. It is bounded from east, south and south east by basement outcrops, while in north it is bounded by a fresh-saline interface occurring in the vicinity of Qattara Depression in the northern part of Egypt (Ezzat, 1974) (Fig. 1). It overlies basement rocks that are crosscut by an extensive E-W fault system in southern Egypt that caused the vertical uplift (Issawi, 1978). In Egypt, it is classified into six distinct geological units ranging in age from Jurassic to Upper Cretaceous (Klitzsch and Lejal-Nicol, 1984) (Fig. 4).

However, the planned area to be cultivated in 1980s was 210.03 km^2 from a total area of 2100.32 km^2 representing the top priority of land capability (GARPAD, 1994). Up till 2003, the total cultivated lands are about 118.81 km^2. The ongoing strategy of development and cultivation project of 924.14 km^2 in East Uweinat needs about 1826 wells beside 58 wells in El-Ain Village (Ministry of Agriculture and Land Reclamation Personal communications). Until 2006, about 383 wells were drilled by the Egyptian Government (Robinson *et al*., 2007).

For more than three decades, governmental experts prepared a strategy for development of East Uweinat area and national plans were settled up. The study area is about 20,437 km^2, which covers the expected future expansion of groundwater exploitation activities. The number of wells drilled in the 1980s had increased dramatically through the 1990s and 2000s periods. For this reason, tracing the spatial distribution of aquifer attributes using the same wells is not available as outgrowths in both lands and well numbers with time, is a matter of fact. However, due to the vast area available for reclamation in East Uweinat, different well spots in different time periods are favorable for determining the aquifer spatial variation. Following this variation will be of prime importance in determining available areas for further horizontal expansion of reclamation projects. Most of the previous studies concentrated their work upon investigation of the aquifer hydrogeological characteristics, but no studies were performed for determining the expected areas suitable for the horizontal expansion of groundwater abstraction projects. Additionally, it had been stated that water management is connected with a series of difficulties such as insufficient information. To overcome these difficulties, the present work was performed to fulfill this information gap through building up a Geographic Information System (GIS) and running-up binary-weighted spatial suitability models (BSSM-WSSM) on the constructed GIS data layers. The BSSM-WSSM models help in determining the priority areas for sustainable hydrogeological development and the possible regions available for future horizontal expansion. The GIS is composed of superposed thematic multilayered system of several decisive maps, which would comprehend in performing the objective of the present work.

MATERIALS AND METHODS

East Uweinat study area occurs at the southwestern part of Egypt, where the water bearing horizons of the NSAS is encountered at shallow depths. This is the only part of this huge aquifer system where groundwater occurs under unconfined conditions in an area where the Nubian sandstone crops out and is underlain by shallow basement rocks; in this area groundwater has no thermal characteristics. The aquifer system has a relatively high hydraulic conductivity and the preliminary assessment of the groundwater resources has indicated that groundwater can be extracted at a rate of 4.7×10^6 m^3 day^{-1}; the long-term economics of extraction that can sustain large-scale development projects (Nour, 1996). The direction of groundwater flow is generally northeastwards but is distorted at faults and fracture zones.

Field and office work: In designing our field study, we considered differences in groundwater consumption history and TDS variation. Accordingly, representative well spots were chosen to reveal the regional spatial distribution of the selected modeled parameters. The hydrogeological background data of the NSAS are undertaken according to the previous published and non-published works and the recently collected data from the inventory carried out for some wells in 2007-2008 (NARSS, 2008). Subsequently, laboratory and office works were conducted, which included mapping and building-up of a multi-layered GIS for topographic elevations, geologic units, basement relief, water chemical analyses and multi-temporal water levels (Table 1-3). The recent well inventories of 2007-2008 included the in situ measurement of pH value, Electric Conductivities (EC), depth to water (mbgl) and collection of water samples for major cations and anions determination and recording the geographic locations of wells by Geographic Positioning Systems (GPS).

The ArcGIS Spatial Analyst extension of ArcGIS 9.1.1® software (ESRI, 2007) was used to develop two spatial models Binary Spatial Suitability Model (BSSM) and Weighted Spatial Suitability Model (WSSM) using the constructed GIS thematic maps. The aquifer transmissivity (T) (m^2 day^{-1}) and hydraulic conductivity (K) (m day^{-1}) were compiled from the results of pumping tests performed by GPC (1984) and GARPAD (1994). These values were plotted on the on the landsat satellite ETM+ image and WSSM map to reveal their spatial distribution and to validate the models' results.

Table 1: Data recorded during 2008 inventory

Well name (Sampled)	pH (1:1)	Ca^{2+} (epm)	Mg^{2+} (epm)	Na^{+} (epm)	HCO_3^- (epm)	Cl^- (epm)	SO_4^{2-} (epm)	EC (dS cm^{-1})	TDS (ppm)	Sodium adsorption ratio (SAR)	Potentiometric level (masl)
4	7.400	3.500	2.300	4.600	0.200	7.300	3.200	1070	685	2.700	241.787
51	7.360	3.200	2.000	4.400	0.200	7.300	2.400	990	634	2.730	234.646
54	7.500	3.000	2.000	4.500	0.200	7.600	2.300	1010	646	2.850	233.789
57	7.320	2.600	1.900	4.600	0.200	7.000	2.100	930	595	3.070	232.094
2	7.170	3.000	2.200	3.500	0.200	6.100	2.600	890	570	2.170	241.000
2/1	7.130	3.200	2.400	3.400	0.200	6.500	2.500	920	589	2.030	248.360
4/1	7.250	3.100	2.200	3.300	0.200	6.000	2.600	880	563	2.020	255.957
6/1	7.150	2.700	1.700	3.600	0.200	5.900	2.100	820	544	2.430	262.800
8/1	7.160	1.200	0.900	2.200	0.100	3.000	1.300	440	282	2.150	272.514
14/1	7.080	2.100	1.200	3.300	0.200	4.100	2.500	680	435	2.570	280.000
7/2	7.250	4.800	3.500	5.100	0.100	4.000	9.400	1350	864	2.500	240.800
S1	7.310	5.900	3.100	4.800	0.300	10.100	3.900	1430	915	2.260	245.100
S2	7.030	4.000	2.700	5.700	0.500	9.000	3.200	1270	813	3.110	242.100
5/3	7.370	3.100	2.000	3.800	0.300	8.500	0.400	920	589	2.380	250.000
3/3	7.350	3.200	2.100	3.900	0.300	8.600	0.600	950	608	2.400	242.550
1/3	7.320	3.000	2.100	3.700	0.200	8.400	0.500	910	582	2.320	250.307
29	7.270	2.700	1.900	3.500	0.200	7.000	1.100	830	531	2.310	237.765
26	7.320	3.800	2.000	4.600	0.200	7.500	2.900	1060	678	2.700	237.548
21	7.150	3.700	2.100	4.500	0.200	7.300	3.000	1050	672	2.640	236.688
17	7.180	3.500	2.500	3.900	0.200	7.000	2.900	1010	646	2.250	243.500
15	7.050	3.300	2.600	3.700	0.200	6.700	2.900	980	627	2.150	237.183
1 (army)	7.090	1.500	1.000	1.800	0.100	2.700	1.600	440	282	1.610	241.000
2 (Kilo)	7.370	2.100	1.200	4.500	0.100	4.300	3.500	790	506	3.500	220.162
4 (Kilo)	7.170	4.000	3.000	4.400	0.300	7.000	4.400	1170	749	2.350	228.107
24 (Kilo)	7.100	3.800	3.000	5.700	0.400	8.500	4.100	1300	832	3.100	221.658
Wataniya	7.160	3.000	2.000	5.500	0.300	7.000	3.500	1080	691	3.470	211.926

Table 2: Data recorded from 1980s period

Well name	Aquifer saturated thickness (m)	Potentiometric level (masl)	Depth to water (mbgl)
PR-IV	431.0	256.9	51.2
Prod-2	141.0	240.7	36.3
PR-II	212.5	248.3	32.7
7A-Obs	60.0	237.5	47.5
Prod-3	71.0	235.4	19.2
Obs-4	37.5	238.6	17.8
Prod-1 Si	200.0	246.0	28.0
PR-I	192.5	247.9	25.3
Obs-3	30.0	235.9	1.6
PR-III	253.5	250.7	38.1
Prod-3 Si	245.0	250.8	38.0
Obs-6	24.0	241.0	0.6
Prod-1	107.0	237.0	11.8
1	363.0	250.0	24.5
2	358.0	250.6	24.6
3	354.0	251.0	25.2
4	351.8	250.0	25.1
5	355.0	255.0	25.4
11	361.6	249.6	25.0
12	359.9	249.0	25.0
13	359.0	248.4	24.5
14	361.7	250.0	24.5
15	360.0	250.4	24.0
16	350.7	248.2	24.0
17	361.0	249.3	24.0
18	361.0	365.2	24.0
19	361.0	247.9	24.8
20	360.2	249.0	23.7
21	358.0	249.2	23.4
22	363.0	249.0	25.0
24	363.0	248.2	24.4
25	364.0	248.5	25.0

The logic steps of suitability spatial modeling could be summarized as:

Table 3: Data recorded from 1990s period

Well name	Potentiometric level (masl)
7A-Obs	237.5
Obs-3	235.9
Obs-4	238.6
Obs-6	227.6
PR-I	247.9
PR-II	248.3
PR-III	250.7
PR-IV	256.9
Prod-1	237.0
Prod-1 Sit	246.0
Prod-2	240.7
Prod-3	235.4
Prod-3 Sit	250.8

- Defining the parameters of prioritization (or goals)
- Decide on evaluation criteria
- Define weights for criteria
- Calculate ranking model results
- Mapping and results evaluation

The priority areas for hydrogeological development and areas suggested for further horizontal expansion should address the following main input criteria:

- Aquifer saturated thickness (m) is adequately enough for the long-term consumption policies
- Depth to water (mbgl) is reasonably shallow and easy to be economically accessed
- Water total dissolved solids (ppm) are satisfactory low for domestic and agricultural purposes

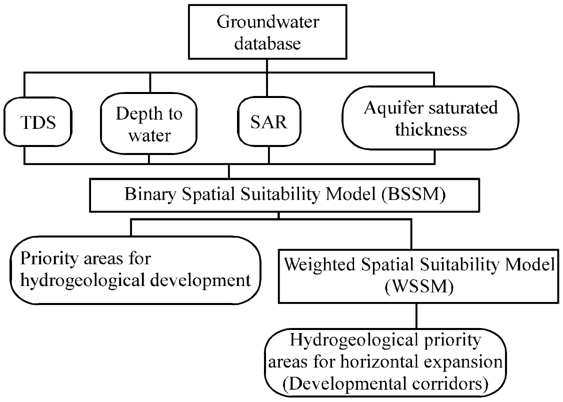


Fig. 5: Flowchart of methodology

Table 4: Ranks and weights for data layers and their influencing classes used for groundwater prioritization mapping

Data layers	Classes	Average rates (rank) (R_f)	Weights (W_f)	Degree of Effectiveness (E)
Groundwater TDS (ppm)	First priority	90	25	22.50
	Second priority	60		15.00
	Third priority	30		7.50
	Fourth priority	10		2.50
Depth to groundwater (mbgl)	First priority	90	25	22.50
	Second priority	60		15.00
	Third priority	30		7.50
	Fourth priority	10		2.50
Groundwater SAR	First priority	90	25	22.50
	Second priority	60		15.00
	Third priority	30		7.50
	Fourth priority	10		2.50
Aquifer saturated thickness (m)	First priority	90	25	22.50
	Second priority	60		15.00
	Third priority	30		7.50
	Fourth priority	10		2.50

- Water Sodium Adsorption Ratio (SAR) is satisfactory low for irrigation purposes

The flowchart of methodology is illustrated in Fig. 5.

One of the most common functions in vector GIS spatial analysis is the classification function. This is used to transform a relatively complex set of vector values to a simpler one. In many respects, this is like using lookup tables in raster classifications, but it accommodates the fact that there is actually only one attribute in a grid that can be used for analysis (Talbot, 1998; Mitchell, 1999; Malczewski, 1999). A range of suitable criteria was chosen and used for classification to create a new grid where all of grid cells are 1 and the rest are 0. In the present work, binary data (presence/absence, spatial distribution of conditional criteria of suitability) are generally assessed using logistic regression methods (Collett, 1991; Miska and Jan, 2005). Logistic regression is a form of Generalized Linear Model (GLM) in which the relationship is expressed as a probability surface, the expected error structure is binomial and a logic transform (logistic link) is applied to the data (Trexler and Travis, 1993; Sokal and Rohlf, 1995; Miska and Jan, 2005). The logistic link means that the probability of obtaining a positive response (meeting the prioritization criteria) is a logistic, s-shaped function when the linear predictor is a first-order polynomial and for second-order polynomials will approximate a bell-shaped function (Crawley, 1993).

In logistic regression, the binary nature of the response variable variation is the basis of parameter estimation and thus the logistic regression models will not produce inappropriate values ($\pi(X)>1$ or $\pi(X)<0$) for the probability of presence. Logistic regression has the form (Hosmer and Lemeshow, 1989) (Eq. 1):

$$\pi(x)=\frac{\exp(\alpha+\beta_x)}{1+\exp(\alpha+\beta_x)} \tag{1}$$

where, α is the constant and β is the coefficient of the respective independent variables. The probability of presence π (ranging from 0 to 1) is given as a function of the vector of this model and becomes apparent after the logistic transformation, giving the form Eq. 2:

$$\ln\left(\frac{\pi(x)}{1-\pi(x)}\right)=\alpha+\beta_x \tag{2}$$

where, (ln) denotes to the natural logarithm (Sokal and Rohlf, 1995). A more technical and detailed review of logistic regression is presented by McCullagh and Nelder (1989) and Collett (1991).

On the other hand, the data manipulation in a Weighted Spatial Suitability Model (WSSM) implies the integration of all thematic layers within the WSSM. However, it was assumed that all these layers have the same magnitude of contribution on the process of suitability determination. Accordingly, the previously mentioned priority factors are assigned equal weights of 25% but with different rates (ranks) and degrees of effectiveness (Table 4). Also some factors work negatively while others work positively in groundwater prioritization, like that in water TDS, depth to water, water SAR, which work negatively in the mapping process, whereas the aquifer saturated thickness works positively in such task. For these reasons, each layer was assigned a specific weight of effect on prioritization mapping. The given weights were adopted, depending on the field observations, the literatures (Akther *et al.*, 2009; Peuquet, 1986; Malczewski, 1999) and the authors' experience. Therefore, the integrated layers in this study were given the weights (W_f), average rates $(R)_f$ and degree of effectiveness (E) of each GIS data layer, as shown in Table 4. The degree of effectiveness was obtained for each priority class according the following equation Eq. 3:

$$E = W_f \times R_f \tag{3}$$

RESULTS AND DISCUSSION

The reported historical data were used to elaborate the change in potentiometric levels, Total Dissolved Solids (TDS) and important hydrogeological characteristics since the implementation of developmental activities in the study area since 1980.

Groundwater movement and potentiometric surfaces: The delineation of groundwater movement was performed GIS data layers of old and recent records of potentiometric levels since the commencement of groundwater well drilling and development activities in the mid-eighties (Fig. 6). These GIS thematic layers constitute the baseline for the assessment of the current status, anticipating changes and forecasting trends in groundwater quantity and quality due to the natural and anthropogenic impacts in time and space. The constructed flow nets clearly show the presence of a change in groundwater movement, regionally and locally. The direction of groundwater movement during eighties period (at the early stage of groundwater abstraction) was generally from the south and the northwest to the east (Fig. 6a). In nineties period,

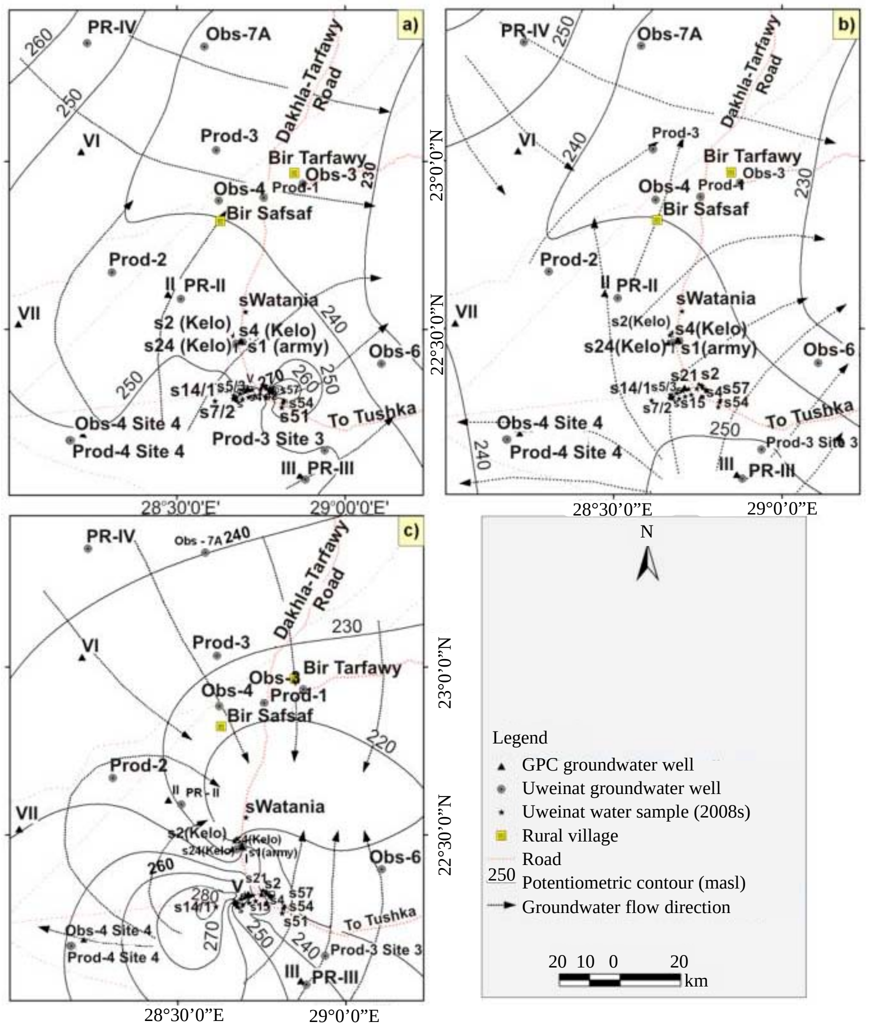


Fig. 6(a-c): Potentiometric levels data through: (a) Eighties period, (b) Nineties period and (c) 2008

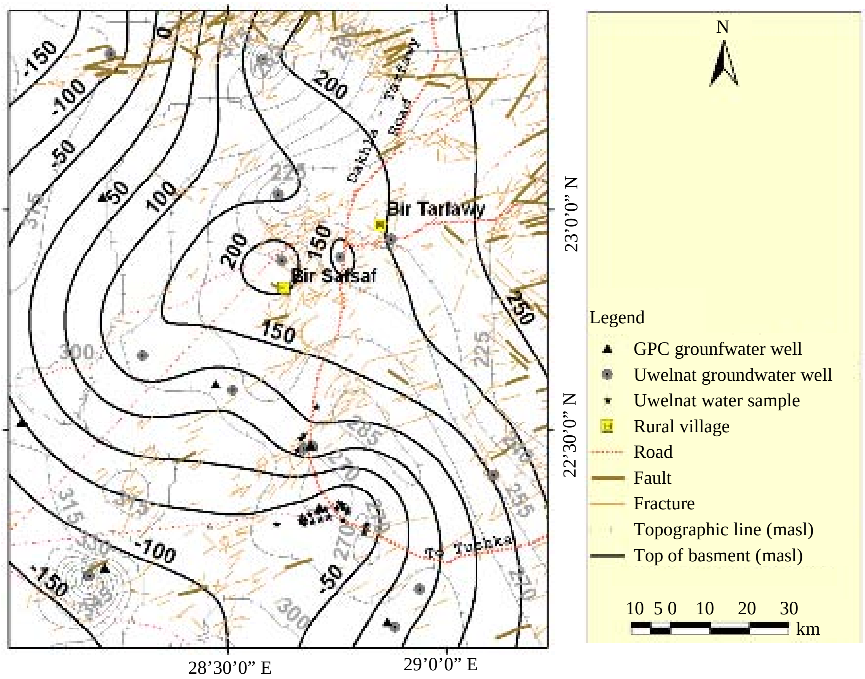


Fig. 7: Structure contour map on top of basement rocks (according to the data of drilled wells)

there was little change where there is a limited movement of groundwater to the west in the southern part of the study area (Fig. 6b). But the dramatic change in the groundwater movement was revealed in the map of 2008, where the potentiometric low area in the middle of the region (bounded by contour 220 (masl)) was formed as a result of the long-term consumption period and the widespread increase in the number of drilled wells. This long-term over drafting led to a drastic depression in potentiometric levels and a reversal in groundwater movement from south and north towards the central part of the mapped area was established (Fig. 6c).

In other words, the maps revealed a certain decline in aquifer water levels, where general stabilized levels prevailed in eighties and nineties periods but with a progressive drawdown in groundwater potentiometric levels from nineties to 2008. Low consumption rates with scarce activities of water well drilling were the reasons behind the slight decline in eighties - nineties periods. The potentiometric levels of the recorded data of the old developmental area during eighties period was about 250 masl, depleted to about 245 masl in nineties period, whereas in 2008, this level became about 230 masl (Fig. 6).

Aquifer saturated thickness: The Six Hills Sandstone Formation represents the sole water-bearing unit in the area, which belongs to the Pre-Aptian age (Said, 1990) (Fig. 4). The presence of semi-permeable layers (clay and siltstone) is discontinuous due to the rapid lateral facies changes. The semi-permeable layers are hydraulically connected. The Six Hills Formation acts as a water bearing bed of sandstone, which is named commonly as the NSAS. The Six Hills Sandstone aquifer is hydraulically connected with the underlying Precambrian fractured basement rocks, as a result of the fracture system, which constitutes secondary porosity zones, but only for shallow depths within the basement.

The estimated thicknesses of this aquifer in subsurface ranges from 186-706 m with an average thickness of about 446 m. From the present field measurements, the thickness variation of this aquifer is mainly due to the structural setting and Precambrian basement relief (Fig. 7), where it occurs at low elevations due south-southwest and northwest (-50-150 masl) which is represented by the effect of numerous fault systems with trends of NE-SW and NW-SE, which configured the basement relief. However, this basement relief variation controls the variation in NSAS saturated thickness, where a substantial increase in thickness is noticeable at the northwest and towards-southwest parts of the study area (Fig. 8), which confirms the previous clue given by the structure contour map constructed on top of basement rocks (Fig. 7).

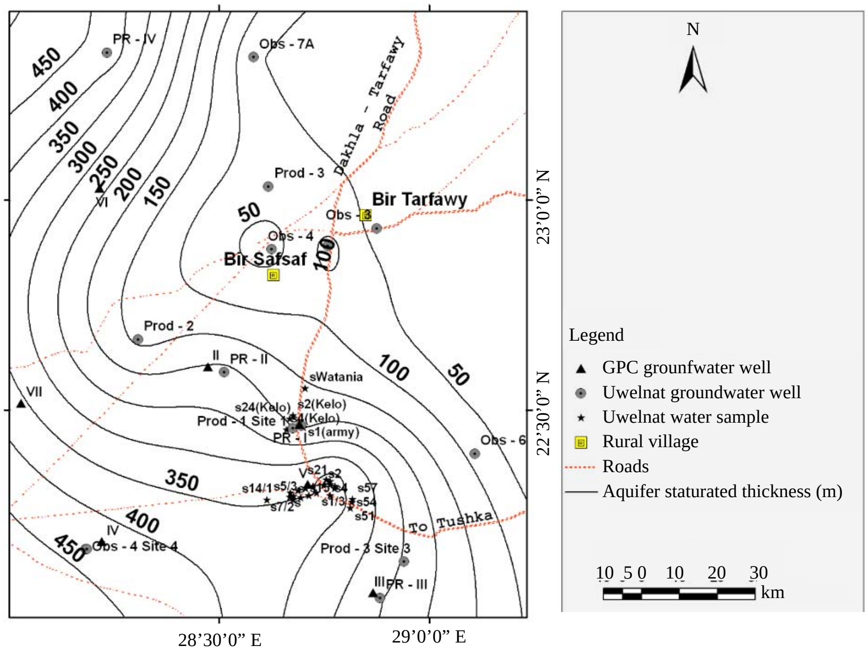


Fig. 8: Saturated thickness of water bearing six hills aquifer system by GIS techniques

Groundwater total dissolved solids (TDS): Total dissolved solids (TDS) are a measure of all constituents dissolved in water. The inorganic anions dissolved in water include carbonates, chlorides, sulfates and nitrates. The inorganic cations include sodium, potassium, calcium and magnesium. Thus, sulfate is a constituent of TDS and may form salts with sodium, potassium, magnesium and other cations (Table 3). As reflected from the data collected in 2008 (Table 1), the salinity content in East Uweinat area is mainly governed by the location of each well. It ranges between 281 mg L^{-1} (Wells 1 Army, 8/1) (analyzed in 2008) and 915 mg L^{-1} (Well S1) (Fig. 9). The variation in groundwater salinity from the year of 2002 until present day was traced by the historical data, where salinities recorded in 2002 and 2008 were mapped (Fig. 9). Sources of TDS in groundwater in the study area originate naturally from the dissolution of rocks and minerals and can also be from the septic tanks and agricultural runoff resulted from the reclamation activities in the last three decades. In the deeper horizons of water bearing sediments, which occur at the northwestern, south and southwestern parts of the study area, the basin-like troughs underlying these parts contain groundwater entrapped in the deeper zones of the basin. These portions of the basin typically contain denser water with higher TDS than the shallower zones (Fig. 7, 8 and 9b-c). Pumping shallow wells may draw up deeper poor quality water into the wells. Accordingly, the noticeable trend is generally towards the relative salinization from 2002 to 2008, which is due to water level depletion and withdrawal of deeper low-quality water in addition to the seepage from the agricultural drainage water (Fig. 9).

Priority areas for hydrogeological development by GIS binary and weighted modeling: To investigate the spatial relationships (topological relationships) of four prioritization or effective hydro-economical attributes that has their own bearing on determining the priority areas for sustainable development and future horizontal expansion, the model is logically based on the previously discussed decision criteria. Topological notions include continuity, interior and boundary, which are defined in terms of neighborhood relations (Egenhofer, 1993). If topological aspects have been part of previous and up-to-date investigations, which constitutes the model input parameters or layers (i.e. depth to groundwater, aquifer saturated thickness, groundwater total dissolved solids and water Sodium Adsorption Ratio (SAR), the definitions of topological relationships have been based upon, or mixed with, other concepts such as metric (Peuquet, 1986) or order (Jungert, 1988; Chang *et al*., 1989; Lee and Hsu, 1992). Consequently, the Binary model codes cells 1 for first priority area, 0 for second priority area, or in other words, it emphasizes the topological relationships by the

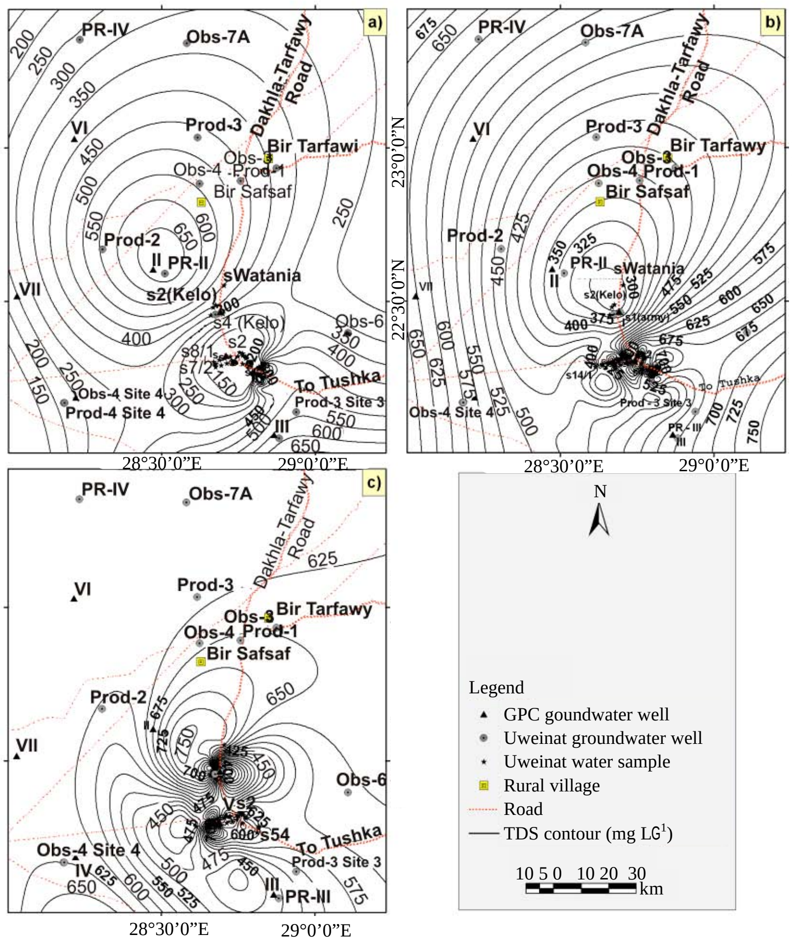


Fig. 9(a-c): Groundwater total dissolved solids, (a) 2002, (b) 2007 and (c) 2008

intersections of boundary and interior of the modeled parameter with the binary values meet and non meet of the prioritization mean value of each input model parameter. The model distinguished areas of first and second priority for the hydrogeological development of the regional east Uweinat area (Fig. 10) as a first step. Thus, the priority areas could be described as integrated roles of these criteria. For a variety of reasons, these priority areas may be determined to be of highest priority for environmental protection and development. For immediate development of the groundwater, priority areas are determined to satisfy the following conditions:

- Water quality segregations (TDS) for agricultural use is satisfactory low (< 620 ppm for the 1st priority area and >620 ppm for the 2nd priority area)
- Economically optimum groundwater depth (< 27 mbgl for the 1st priority area and >27 mbgl for the 2nd priority area)
- Sodium Adsorption Ratio (SAR) as a value determining the water suitability for agriculture (< 2.5 for the 1st priority area and >2.5 for the 2nd priority area)
- Aquifer saturated thickness is big enough for the long-term consumption (>280 m for the 1st priority area and <280 m for the 2nd priority area)

The running of the GIS binary spatial suitability modeling (BSSM) technique elucidated two (1st and 2nd) priority areas (subclasses) for hydrogeological development. The 1st priority area, which meets the predetermined criteria of prioritization, occupies mostly the south-central and southwestern parts of the study

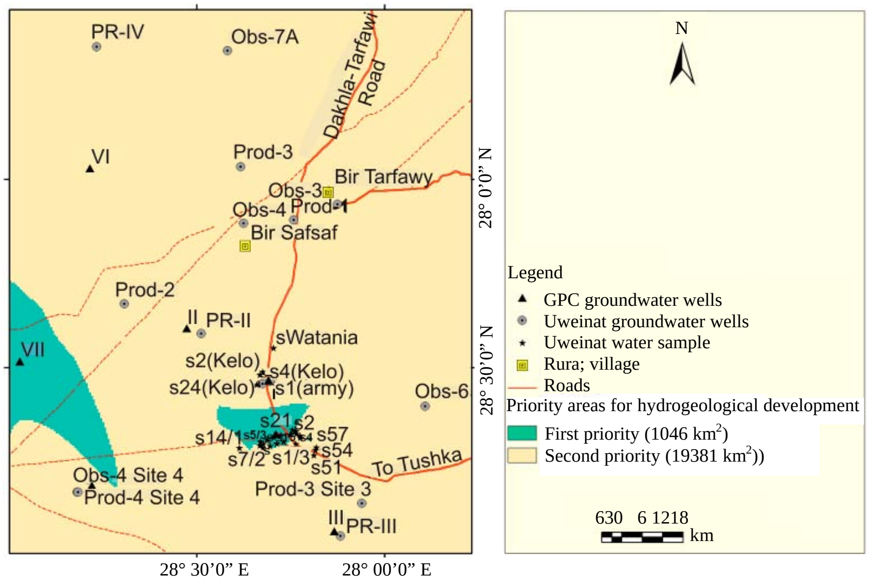


Fig. 10: Determining priority areas for sustainable hydrogeological development by BSSM technique, according to the data acquired in 2007-2008

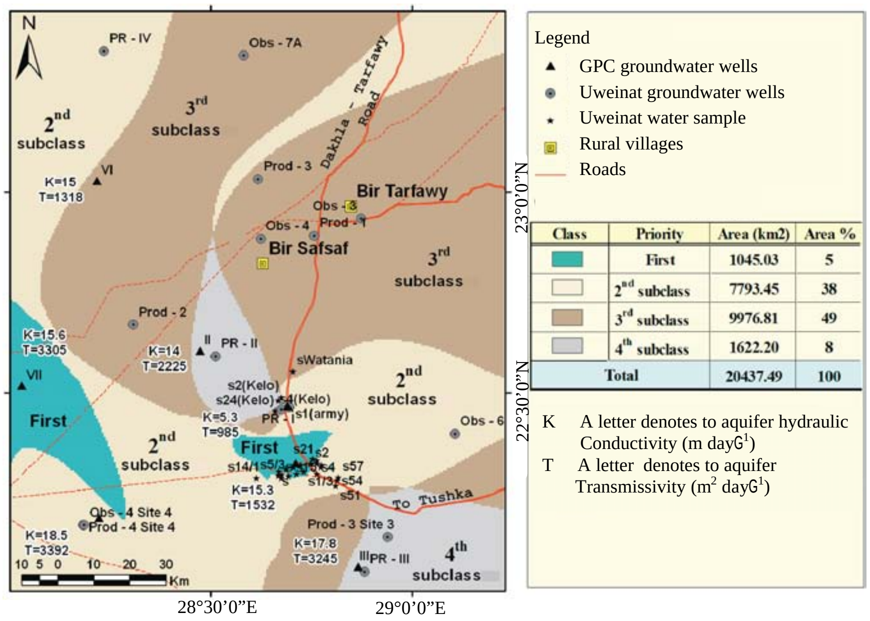
area with an area of 1,046 km^2 which represents 5.12% of the total study area. The 1st priority area occupies mostly the intensively developed area characterized by heavy consumption of groundwater and pivotal irrigation schemes, which reflects the accuracy of the model results. However, most of the mapped area percentage is covered by the 2nd priority area (94.88% of the total study area) (Fig. 10).

In the second step, the spatial analysis was performed on these layers through a WSSM to discriminate more subdivisions for the 2nd priority area resulted from the BSSM, or, in other words, determining the suitable areas available for further horizontal expansion in reclamation activities (Fig. 11). Accordingly, as our aim is to identify the suitable areas for new horizontal expansions in development activities, so the 2nd priority area should be classified or subdivided into more classes using the weighted overlay GIS model. From this point, the BSSM technique was used at the early stage of the GIS spatial modeling. Subsequently, it was followed by the weighted overlay tool (ArcGIS Spatial Analyst Extension) using the same input criteria described previously, within the Raster Calculator of ArcGIS 9.3.1® software platform. Equal weights were assigned to each thematic input data layer (25% for each layer) (Table 4).

The WSSM output identified three more priority classes derived from the 2nd priority area, namely, the 2nd (7793 km^2), 3rd (9976 km^2) and 4th (1622 km^2) priority classes, which represent more subdivisions for the 2nd priority area resulted from the BSSM. The geographic locations of the 2nd priority class represent new proposed suitable areas for development far from the old reclaimed ones (Fig. 11).

To validate the BSSM-WSSM results, some values of the Transmissivity (T) and hydraulic conductivity (K) has been collected (GPC, 1984; GARPAD, 1994) and plotted on the WSSM map (Fig. 11). It was found that the spatial distribution of these values is consistent with the distribution of proposed priority areas for horizontal expansion. Accordingly, the 2nd and 3rd subclasses are characterized by high T values (i.e., 1533 m^2 day^{-1} in Well S14; 2225 m^2 day^{-1} in Well Prod-2; 3392 m^2 day^{-1} in Prod-4-site 4). These priority subclasses are suitable for future horizontal expansion and are characterized by reasonable aquifer saturated thickness (i.e., 350, 150, 230 and 425 m, respectively). However, the WSSM also pinpointed to reasonable TDS values in these areas (i.e., 450, 600, 550 and 625 ppm, respectively.

Special attention is given to connectivity of the boundaries of these priority areas to preserve the hydrogeological characteristics of this aquifer system. The results of WSSM will guide planners to maintain these hydro-environmentally sensitive areas. The model predicts areas that can economically accommodate the future sustainable development and horizontal expansion of East Uweinat area.



Class	Priority	Area (km2)	Area %
🟦	First	1045.03	5
▯	2nd subclass	7793.45	38
🟫	3rd subclass	9976.81	49
▨	4th subclass	1622.20	8
Total		20437.49	100

K A letter denotes to aquifer hydraulic Conductivity (m day^{-1})

T A letter denotes to aquifer Transmissivity (m^2 day^{-1})

Fig. 11: Determining priority areas for sustainable hydrogeological development by WSSM techniques, according to data acquired in 2007-2008

CONCLUSION

The Nubian Sandstone is a significant aquifer system that is used to supply water for agricultural and domestic purposes in East Uweinat area. The present work aims to determine the hydrogeological priority areas of development suitable for further horizontal expansion. For such a critical purpose, the hydrogeochemical data of the most economically effective attributes are analyzed and digitized within a multilayered GIS. The attributes that had been taken into consideration are depth to water, aquifer saturated thickness, water TDS and SAR. The database of recorded water levels included those measured in the 1980's, 1990's and 2008, which showed that the potentiometric levels had a general noticeable decline from 1980's through 2008. The upgradable constructed GIS and binary-weighted spatial suitability models (BSSM-WSSM) were performed for determining the priority areas for sustainable hydrogeological development and the possible areas available for future horizontal expansion of reclamation projects. The BSSM model's output map elucidated that the 1st priority area comprises mostly the intensively developed old reclaimed area that is characterized by a big number of production wells and consequently, heavy consumption of groundwater. Most of the study area was categorized as the 2nd priority area (94.88%), which designates to a lesser aquifer quality and characteristics in terms of the given prioritization criteria. For more detailed classification, the WSSM identified three more priority subclasses subdivided from the 2nd priority area, namely, the 2nd (7,793 km^2), 3rd (9,976 km^2) and 4th (1,622 km^2) priority subclasses. The geographic locations of the 2nd priority class represent new proposed development areas relatively far from the present crowded ones, which could relieve the high pressure exerted upon the aquifer system in such areas. However, additional expansion in reclamation projects due north and east directions needs additional researches to assess the exact responses of the aquifer to the overgrowing withdrawal policies. Further accelerated drawdown in future is highly expected if continuing the present-day heavy consumption rates in the same present day consumption areas or even if the reclamation and agricultural projects are expanded without control on the kinds of crops to be planted.

As a consequence of the growing investments and populations, many new villages and communities had been evolved in East Uweinat area, which led to an urgent need for a well-developed water economy. The water economy is characterized by limited opportunities for new water impoundments, rising incremental water supply costs, intensified competition between diverse users and increased interdependencies among water users. Also there is an urgent need for providing information for improvements in the planning, policy and management of groundwater resources. Furthermore, groundwater in East Uweinat developmental area is mostly found under unconfined (water table) conditions thereby is liable to contamination by the agrochemicals and domestic waste water leaks.

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