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Integration of Multivariate Analysis and Spatial Modeling to Assess Agricultural Potentiality in Farafra Oasis, Western Desert of Egypt

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PRECISE assessment of land and water resources in the newly reclaimed desert land in Egypt is a pillar of sustainable agricultural production. The principal component analysis (PCA), factor analysis (FA) and spatial modeling were integrated to develop a GIS-based model for agricultural potentiality in Farafra Oasis, Western Desert of Egypt. The studied area (167.98 km^2, i.e. 16798 ha) is located between 27° 01' 35.71" to 27° 10' 5.38" N and 28° 16' 34.95" to 28° 22' 58.71" E. Twenty-two soil profiles were dug, and samples were collected and analyzed. Groundwater samples were collected from ten wells and analyzed. Slope, aspect, surface roughness, and topographic wetness index were extracted from a digital elevation model. The groundwater showed no limitations for irrigation. Soil properties and topographic attributes showed linear correlations among each other. The results of the PCA/FA were sufficient to estimate a weight for each parameter. The most effective factors determining agricultural potentiality were soil physical properties (0.36) followed by chemical properties (0.31) and topography (0.26), while erosion was the least one (0.07). The GIS-based model showed that the area belongs to moderate (62%) and high potentiality (35%) classes under sprinkler irrigation, while moderate (1%), high (94%) and very high potentiality (2%) under drip irrigation. Combined use of multivariate and spatial analysis would help in developing sustainable agricultural strategies in such desert areas.

Keywords: Multivariate analysis; Spatial modeling; GIS; Farafra Oasis; Western Desert.

Introduction

Ensuring food security isa critical global challenge in recent years, especially in developing countries. The agricultural sector is expected to play a vital role in providing sustainable food production (Pawlak and Kolodziejczak, 2020). However, the current situation of food supply in Egypt is complicateddue to ever-growing population with limited cultivated land and water scarcity (Zahran, 2020). Furthermore, the urban encroachment on the fertile land in Egypt would cause a 36% crop production loss by 2030 (Hanjra and Williams, 2020).

In 2015, the Egyptian government initiated a national project to reclaim 630,252 ha mostly in the Western Desert Region (Moghazy and Kaluarachchi, 2020), which occupies over two-thirds (68%) of the Egyptian total land area (El-Ramady et al., 2019). This area gained attentions in the newly reclaimed zones owing to its unique features that enables sustainable agricultural development (Alary et al., 2018). This region hasa priority due to presence of the Nubian Sandstone Aquifer (NSA) that provides adequate groundwater supply (Fadl and Abuzaid, 2017). The region also includes several Oases with fertile soil developed by intercalated fluvial and aeolian deposits (Elbasiouny and Elbehiry, 2019). According to DRC (2018), Farafra Oasis is one of the promising areas and a prime target for such expansion plans. Therefore, precise assessment of agricultural potentiality considering topographic features, soil properties and water quality is necessary for sustainable production.

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Over widedesert areas, geospatial technologies such as remote sensing (RS) and geographic information system (GIS) provide modern efficient tools to acquire data needed for natural resources assessment (Abuzaid & Fadl, 2016 and Fadl & Sayed, 2020). Both RS and GIS are two techniques that can be integrated to enhance each other (Mohamed and Gouda, 2018). Compared with intensive filed surveys, RS is a cost-effective and time-efficient tool for extractinga large amount of data related to soil and terrain features as well as land under various land use/land cover types (Kumar, 2018). GIS can store, manipulate and organize these kinds of data into topics or themes that represent the multiple aspect of complex environmental issue (Aldabaa and Yousif, 2020). Combined use of RS and GIS can integrate spatially referenced datasets to be included in spatial modeling (AbdelRahman et al., 2017).

According to Reddy (2018), spatial modeling is "an analytical process conducted in conjunction with a GIS in order to describe basic processes and properties for a given set of spatial features". This approach enables studying and simulating spatial phenomena that occur in the real world that in turn facilitate solving of problems and planning (Awange and Kiema, 2019). Developing a dynamic spatial model requires integrating a given set of factors and their relative importance or "weights" to make the results more real (Mohamed et al., 2019). In environmental studies, multivariate statistical analysis, including principal component analysis (PCA) and factor analysis (FA) are most effective for such a purpose (Jahin et al., 2020). The PCA/FA depends mainly on the current data provided for the analysis that allows modifying the weights in response to spatial and temporal variations in environmental conditions (Härdle and Simar, 2015). Previous studied affirmed the reality of PCA/FA in assessing land resources in many areasin Egypt such as north Nile Delta (Abuzaid and Bassouny, 2018; Abuzaid et al., 2021) and northwestern coast (Mohamed et al., 2020). Hence, integrated use of PCA/FA and spatial modeling would make the results more representative and closer to reality. The current work aimed at using PCA/FA in conjunction with GIS spatial analyst for developing a GIS-based model for assessing agricultural potentiality in Farafra Oasis. The model would provide an insight into efficient land-use planning in the newly reclaimed desert areas.

Materials and methods

Study area

The study was conducted within 167.98 km^2 (16798 ha) in Farafra Oasis, one of the inland oases in the Egyptian western desert. The geographic location is in UTM zone 35 between longitudes 28° 16' 34.95" to 28° 22' 58.71" E and latitudes 27° 01' 35.71" to 27° 10' 5.38" N (Fig. 1). The climatic data (Average of ten years from 2005 to 2015) collected from Farafa station indicate that the minimum temperate is 4.9 °C and occurs during January, while the highest one is 38.5 °C and occurs during July. The mean annual temperature is 22.6 °C and the total annual rainfall is 12.7 mm. According to Soil Survey Staff (2014a), the soil temperature regime is "Hyper-thermic" and the soil moisture regime is "Torric".

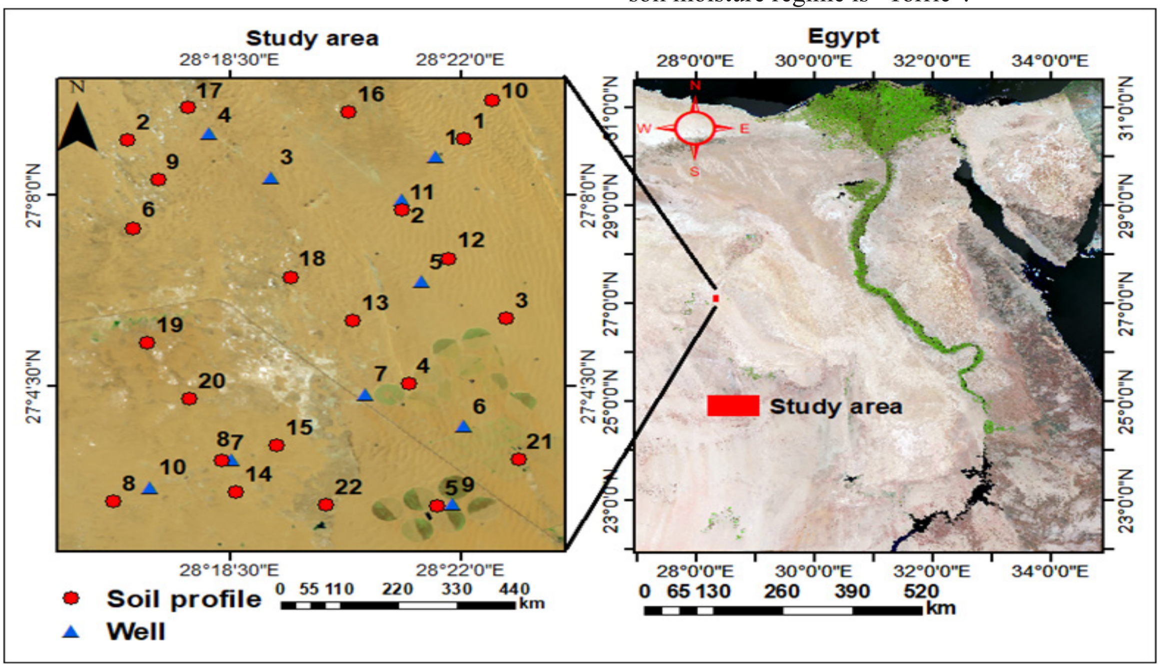

Fig. 1. Location maps and soil profile locations in the studied area

Remote sensing and GIS work

One scene (path 178 / row 41) of Landsat 8 operational land imager (OLI) was acquired from the USGS Earth Explorer gateway (http://earthexplorer.usgs.gov/) on 21-9-2020. The digital processing of the OLI image was performed using ENVI 5.1 software, including atmospheric correction (FLASH module), stretching, band stacking, and spatial and spectral subsets. Thereafter, an unsupervised classification (ISO DATA classifier) followed by a supervised classification (maximum likelihood) was executed. A 1:100,000 topographic map sheet covering the area was scanned and geo-referenced (UTM projection, Zone 35 and WGS-84 datum) within ArcGIS 10.8 software (ESRI Co, Redlands, USA). The spot heights and contour lines were digitized and used for generating a raster digital elevation model (DEM) using topo to raster interpolation method.On the light of the processed OLI image, geological map (CONCO-Coral/EGPC, 1987), DEM, and field survey, the different landforms was delineated (Zinck et al., 2016). The topographic features; slope, aspect, surface roughness index (SRI), and topographic wetness index (TWI) were extracted from the DEM. The SRI was calculated using the focal statics (Fenta et al., 2020) as flows:

$$SRI= \frac{DEM_{Mean}-DEM_{Min}}{DEM_{Max}-DEMmin}$$

The TWI was calculated according to Haghighi et al. (2021) as follows:

$$TWI = Ln\left(\frac{As}{\tan\beta}\right)$$

where A_s is the is the local upslope contributing area derived from flow accumulation raster and β is slope raster.

Field work and laboratory analysis

Twenty-two geo-referenced soil profiles (Fig. 1) were dug to a 150 cm depth or lithic contact. General features of each profile were extensively observed according to FAO (2006). Soil samples (58 samples) were collected from the subsequent horizons. Ten groundwater samples were collected from ten artesian wells (Fig. 1) after operating the wells for about 10 minutes. pH, electrical conductivity (EC) and total dissolved solids (TDS) were measures in-situ using a portable HACH instrument (HQ 40d, multi, USA). The samples were collected in acid-washed high-density polypropylene bottles (1 L). For heavy metals analysis, another set of water samples were collected in 500 mL polypropylene bottles previously washed with 50% HNO_3 then double deionized water, and acidified with 5 mL HNO_3. Other parameters were further analyzed in laboratory according to APHA (2017).

Soil samples were air-dried, ground, passed through a 2-mm mesh and kept for analyses. Soil analyses were performed according to standard methods of Soil Survey Staff (2014b). The analyses included particle size distribution using pipette method), pH in 1 : 2.5 soil : water suspension), EC in soil paste extract, organic matter (OM) using Walkley-Black procedure, calcium carbonate using calcimeter, gypsum content using acetone method, cation exchange capacity (CEC) and exchangeable sodium percentage using ammonium acetate method.

Assessment of agricultural potentiality

This procedure includes three steps (Fig. 2); selection of indicators representing potentiality factors (soil, topography, and erosion), developing an index for each factor, and combining the four factors in a single map.

The first step

The widely accepted parameters affecting land suitability for irrigated agriculture were selected based on literature. In order to obtain one value for the whole soil profile, weighted mean value (WMV) for soil physiochemical properties (gravel content, sand, silt, clay, EC, $CaCO_3$, gypsum, OM and ESP) was calculated by multiplying value of the property by the thickness of soil horizon and dividing the resultant by the total depth of soil profile.

The second step

In this step, four indices were developed to quantifythe fitness of physical soil index (PSI), chemical soil index (CSI), and topographic index (TI) to two modern systems of irrigation, i.e. sprinkler and drip irrigation. The PSI, CSI and TI was computed using theStorie index rating; one of the parametric-approach methods provided by Storie (1978) as follows:

$$\mathrm{Idex_x} = \left[\left(\frac{R_1}{100}\right)\times\left(\frac{R_2}{100}\right)\times\left(\frac{R_n}{100}\right)\right]\times 100$$

where x is the index, R_1, R_2, and R_3 is the ratings of the selected parameters, and n is the number of selected parameters within each index.

According to El-Baroudy (2016), rating isa numerical term explainshow as location supports a specific land use, and there is no standards for rating criteria of each factor. Hence, in the current work, the parameters were rated based on expert's suggestions and a review of literature in arid regions (Albaji et al., 2010; Albaji et al., 2015; FAO, 1985; Haghighi et al., 2021; John et al., 2021; Kalogirou, 2002; Özkan et al., 2020; Van Ranst and Ann Verdoodt, 2005) as shown in Table 1.

The fourth index; erodibility index (ErI) has a similar effect under different types of irrigated agriculture. Thus its rating remained similar under sprinkler and drip irrigation. The ErIwas represented by the erodible fraction EF (Mg ha^{-1} $year^{-1}$) that was calculated using the equation suggested by Fenta et al. (2020) as follows:

$$EF = \frac{29.09 + 0.31SA + 0.17SI + 0.33\frac{SA}{CL} - 2.59SOM - 0.95CaCO_3}{100}$$

where SA is the sand content, SI is the silt content, CL is the clay content, OM is the organic matter content. The EF ranges from 0 to 1.0, where the soil erodibility is classified as very slight (EF < 0.1), slight (0.1 ≤ EF < 0.4), moderate (0.4 ≤ EF < 0.5), high (0.5 ≤ EF < 0.7), and very high (EF > 0.7)(Borrelli et al., 2014; Guo et al., 2017). Accordingly, these classes were assigned ratings of 100, 95, 85, 60 and 40, respectively (Table 1).

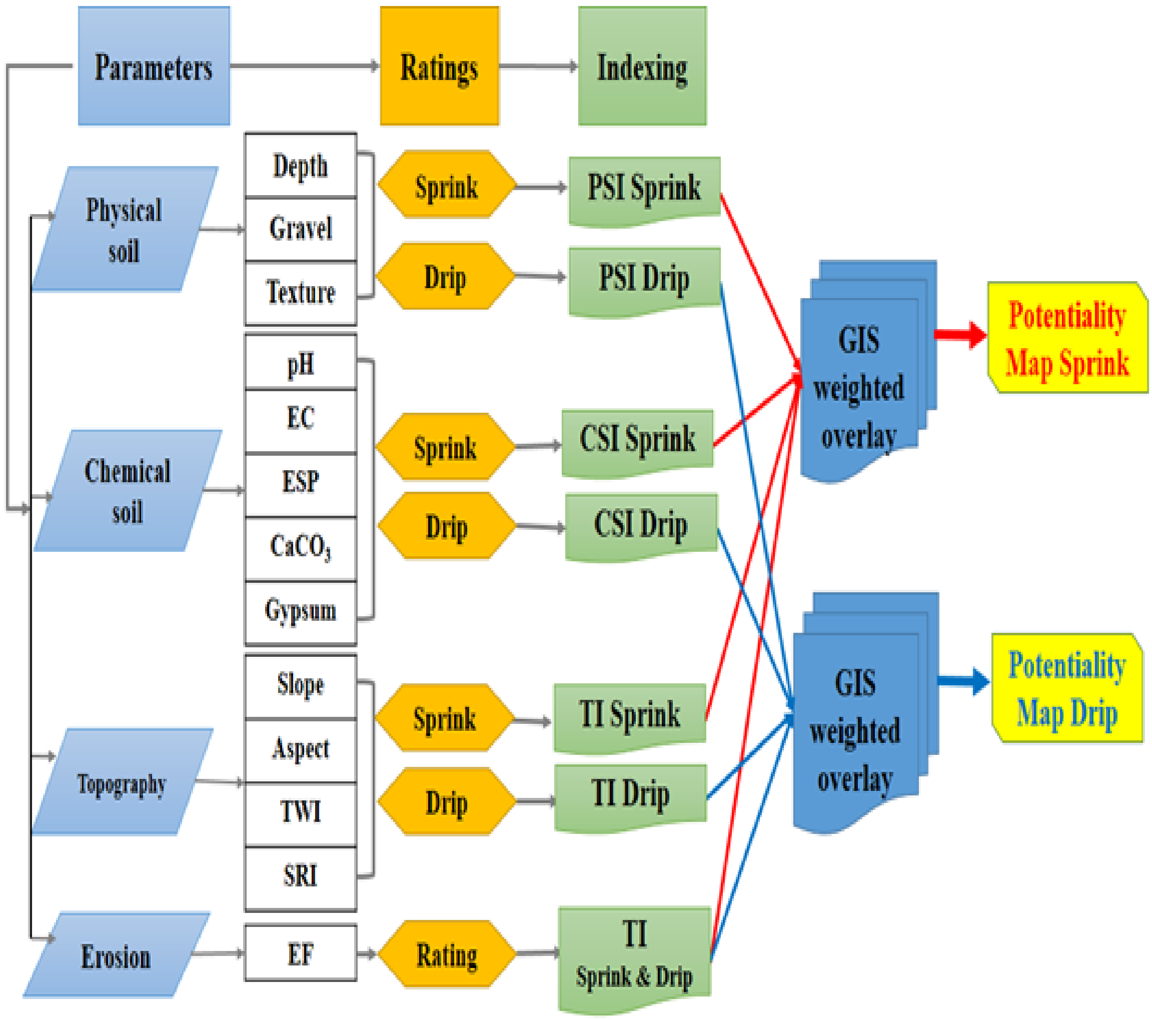

Fig. 2. Flowchart of the methodology used in the current work

TABLE 1. Ratings of the selected characteristics

Index	Criteria	Value	Score Sprink	Score Drip	Factor	Criteria	Value	Score Sprinkle	Score Drip
Physical soil index (PSI)	Depth, cm	< 20	30	35	Chemical soil index (CSI)	pH	6.6 - 7.3	100	
		20 - 50	65	70			7.3 - 7.8	95	
		50 - 80	85	90			7.8 - 8.4	85	
		80 - 100	95	100			8.4 - 9.0	60	
		> 100	100	100			> 9.0	40	
	Gravel,%	< 5	100			EC, dS m^{-1}	< 4	100	100
		5 -- 15	95				4 -- 8	95	95
		15 - 40	85				8 -- 16	85	85
		40 - 80	60				16 - 30	75	75
		> 80	40				> 30	65	65
	Texture	CL, SiL	100	100		ESP	< 10	100	100
		SCL, SC	95	95			10 - 15	85	95
		L, SiL, Si	90	90			15 - 30	60	85
		SL	90	95			30 - 50	40	60
		SiC, C	85	85			> 50	25	40
		LS	70	85		$CaCO_3$, g kg^{-1}	< 3	90	90
		S	50	70			3 - 100	95	95
	Slope, %	< 5	100	100			100 - 250	100	95
		5 -- 8	95	100			250 - 500	90	80
		8 -- 16	85	90			> 500	80	70
		16 - 30	70	75		Gypsum, g kg^{-1}	< 3	90	90
		> 30	50	55			3 - 100	100	100
Topographic index (TI)	Aspect	North	100				100 - 150	90	85
		South	95				150 - 250	85	80
		Flat	85				> 250	75	70
		East	60		Erosion risk index (ErI)	EF	< 0.1	100	
		West	40				0.1 - 0.4	95	
	TWI	> 5	100				0.4 - 0.5	85	
		5 - 4	95				0.5 - 0.7	60	
		4 - 3	85				> 0.7	40	
		3 - 2	60						
		< 2	40						
	SRI	< 0.2	100						
		0.2 – 0.4	95						
		0.4 – 0.6	85						
		0.6 – 0.8	60						
		> 0.8	40						

CL, clay loam; SiL, silt loam; SCL, sandy clay loam; SC, sandy clay; L, loam; SiL, silt loam; Si; silt; SL, sandy loam; SiC; silt clay; C, clay; LS, loamy sand; S, sand; TWI, topographic wetness index; SRI, surface roughness index; EC, electrical conductivity; ESP, exchangeable sodium percentage; EF, erodible fraction.

The final step

A GIS-based model was implemented to produce two maps for the agricultural potentiality under the two irrigation systems. A vector layer of each index was generated using a modal profile representing each unit. The vector layers were converted to raster format. They were reclassified into fiveclasses; very high (>80), high (80 – 60), moderate (60 – 45), low (45 – 30), and very low (<30). These intervals are corresponding to the classes proposed by FAO (1985), i.e. highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not-suitable (N1), and permanently not-suitable (N2), respectively. Finally, the four layers were superimposed using the weighted overlay model. The weight of eachindex was assigned based on the results of PCA/FA.

Statistical analysis

The PCA/FA was performed on fifteenpropertyof soil and terrain attributes using IBM SPSS statistical package for Windows version 25. Before performing the analysis, all variables were subjected to normalization by calculating their z-scores. Tripathi and Singal (2019) reported that the normalization step is of special concern to environmental data because the parameters have different units, and thus such normalization makes no sense to aggregate two values with different units. Thereafter, the linear relationships between the created z-scores were checked using the Pearson's correlation coefficient. The FA was applied on the correlation matrix using the principle component extraction method and Varimax rotation, and only factors having eigenvalues > 1.0 were considered. The weight of each parameter was calculated as a ratio of communality of each indicator to the sum of all indicator communalities as outlined by Jahin et al. (2020).

Results and Discussion

Groundwater suitability for irrigation

Results in Table 2 reveal that the pH values of the groundwater samples ranged from 6.67 to 8.30, which in the desirable range for irrigation purposes (6.5 – 8.4) as suggested by Ayers and Westcot (1994). The EC varied from 0.27 to 0.42 dS m^{-1}, while the SAR ranged from 0.44 to 1.01. This indicates none degree of restrictions on use in irrigation concerning salinity or infiltrations problems (Ayers and Westcot, 1994). Regarding the specific ions toxicity, neither Na^+ nor Cl^- would pose potential risks when used under drip of sprinkler irrigation, since their values were below safe limits for irrigation, i.e. 3 mmolc L^{-1}(Ayers and Westcot, 1994). The concentrations of HCO_3^- (less than 1.5 mmolc L^{-1}) indicated no restriction of use under overhead sprinkler irrigation (Ayers and Westcot, 1994). Values of the residual sodium carbonate (RSC) were below 1.25 mmolc L^{-1}, indicating that the groundwater are safe to be used for irrigation purposes (US Salinity Laboratory Staff, 1954). Results of the groundwater analyses show the high potentiality of water resources in the studied area.

TABLE 2. Analyses of the collected groundwater samples

No	pH	EC dS m^{-1}	Soluble cations, mmolc L^{-1}				Soluble anions, mmolc L^{-1}				SAR	RSC mmolc L^{-1}
			Ca^{2+}	Mg^{2+}	Na^+	K^+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}		
1	8.10	0.35	1.27	1.41	0.57	0.25	0.00	1.00	2.00	0.50	0.49	-1.68
2	7.49	0.36	0.77	1.64	0.65	0.54	0.00	1.00	2.00	0.60	0.59	-1.41
3	6.67	0.27	1.33	0.48	0.77	0.12	0.00	1.00	1.20	0.50	0.81	-0.81
4	6.68	0.29	1.33	0.59	0.86	0.12	0.00	1.00	1.50	0.40	0.88	-0.92
5	6.83	0.30	1.00	1.01	0.89	0.10	0.00	1.00	1.50	0.50	0.89	-1.01
6	7.53	0.34	1.30	0.93	0.71	0.46	0.00	1.00	1.50	0.90	0.67	-1.23
7	8.30	0.31	1.49	1.00	0.49	0.12	0.00	1.10	1.50	0.50	0.44	-1.39
8	7.40	0.42	1.44	1.39	1.19	0.18	0.00	1.20	2.00	1.00	1.01	-1.63
9	8.30	0.33	1.45	0.91	0.70	0.44	0.00	1.10	1.40	0.85	0.64	-1.26
10	7.48	0.34	1.13	1.10	1.00	0.10	0.00	1.20	1.80	0.23	0.95	-1.03

EC, electrical conductivity; SAR, sodium adsorption ratio, RSC, residual sodium carbonate

Geomorphology and soils

The studied area includes six landforms, i.e.pediplain, sand sheets, alluvial terraces, depression, rock outcrops, and hills (Table 3 and Fig. 3). The pediplian is the predominant landform and covers an area of 67.28 km^2, representing 40.05% of the total area. This landform is composed of three units; high, moderate and low covering 0.79, 38.03 and 1.23% of the total area, respectively. The main soils within this landform are Lithic Torripsamments (57%), Lithic Torrorthents (29%) and Lithic Haplocalcids (14%). The sand sheet is the second dominant landform with an area of 53.86 km^2, representing 32.06% of the total area. This landform includes four units, i.e. high, moderately high, moderate, and low that cover 2.18, 17.38, 0.41 and 12.08% of the total area, respectively. The soils are classified as Typic Torripsamments. The alluvial terraces rank the third dominant landform and cover an area of 37.53 km^2, representing 22.34% of the total area. This landform includes a series of terraces (high, moderate and low) occupying 14.31, 3.06 and 4.97% of the total area, respectively. According to Hamdan and Hassan (2020), the formation of these terraces is attributed to the sedimentation process of the Palaeofluvial deposits during fluvial periods. The main soils within this landform are Sodic Haplocalcids (60%), Typic Haplocalcids (20%), and Typic Torriorthents (20%). The depression landformranks the fourth predominant landforms that occupies 4.65 km^2 in the north western part, covering 2.77% of the total area. The soils are classified as Typic Torripsamments. The rock outcrops is the fifth abundant landform in the area and is distributed in different polygons in the middle and northwestern parts, covering an area of 3.11 km^2, i.e. 1.85% of the total area. The isolated hills covers 1.58 km^2 in the eastern parts, representing less than 1% of the total area.

Soil properties

The weighted mean values of soil properties are presented in Table 4. Results show that the soil depth ranged from 10 to 150 cm, indicating that the soils were very shallow to very deep. The soils had a very few to common gravel content with a range of 2.19 to 14.62%. The soil pH varied from 7.39 to 8.53, while the EC ranged from 1.15 to 27.05 dS m^{-1}. These ranges indicate that the soils were slightly to moderately alkaline and non-saline to strongly saline (Soil Science Division Staff, 2017). Calcium carbonate and gypsum contents varied from 26.01 to 268.80 g kg^{-1}and from 0.92 to 77.41 g kg^{-1}, respectively. According toFAO (2006), the soils were moderately to extremely calcareous and slightly to moderately gypsiferous. The OM content was very low and did not exceed 10 g kg^{-1} due to aridity and absence of vegetation. The CEC ranged from 0.65 to 6.50 cmolc kg^{-1}, indicating a very low to low exchange capacity (Hazelton and Murphy, 2016). The ESP varied from 5.80 to 27.84, indicating none to moderate sodicity hazards (FAO, 1988). The sand dominated the soil particle size distribution averaging nearly 82% of the fine earth flowed by silt (15%), while clay was the least abundant fraction (3%). The EF values ranged from 0.49 to 0.92, indicating a moderate to very high erodibility. Such higher EF values are due to low clay and organic matter contents, which play a crucial role in protecting soil against erosion hazards (Guo et al., 2017).

TABLE 3. Landforms and soil taxonomy in the studied area

Landform	Unit	Area, km^2	Area, %	Profile	Soil Taxonomy
Alluvial terraces	High	24.04	14.31	1	Typic Haplocalcids
				4, 11	Sodic Haplocalcids
	Moderate	5.14	3.06	7	Sodic Haplocalcids
	Low	8.35	4.97	9	Typic Torriorthents
Pediplain	High	1.33	0.79	21	Lithic Torrorthents
	Moderate	63.89	38.03	16, 18, 22	Lithic Torripsamments
				19	Lithic Haplocalcids
				20	Lithic Torriorthents
	Low	2.06	1.23	17	Lithic Torripsamments
Sand sheet	High	3.67	2.18	10	Typic Torripsamments
	Moderately high	29.20	17.38	3, 5, 12	
	Moderate	0.69	0.41	13	
	Low	20.30	12.08	8, 14, 15	
Depression	---	4.65	2.77	2, 6	
Rock outcrops	---	3.11	1.85	---	---
Isolated hills	---	1.58	0.94	---	---

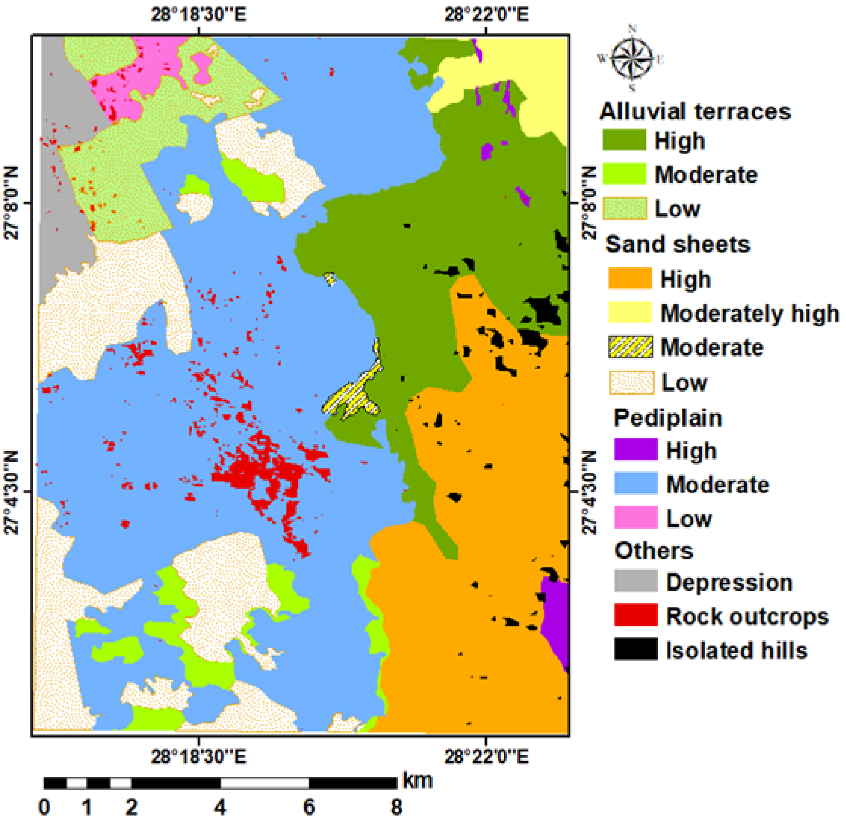

Fig. 3. Geomorphic units map of the studied area

TABLE 4. Weighted mean values of soil properties of the studied profiles

Profile	Depth, cm	Slope, %	Gravel, %	EF	pH	EC dS m^{-1}	$CaCO_3$, g kg^{-1}	Gypsum, g kg^{-1}	OM, g kg^{-1}	CEC cmolc kg^{-1}	ESP	Sand, %	Silt, %	Clay, %	Texture
1	150	3.22	4.62	0.54	8.53	1.15	183.70	12.02	1.79	2.98	10.40	57.85	39.15	3.00	Sandy loam
2	140	0.00	6.95	0.62	7.67	9.94	258.15	4.69	2.16	2.78	6.15	87.99	9.92	2.48	Sand
3	120	2.44	2.63	0.58	7.80	13.17	170.48	4.70	2.35	3.23	6.99	91.15	4.69	4.17	Sand
4	150	9.39	4.11	0.92	8.11	2.28	199.38	27.38	1.95	1.08	15.66	64.61	34.90	0.49	Sandy loam
5	140	0.98	3.62	0.80	8.14	6.09	161.98	10.82	2.24	0.83	15.85	97.60	1.24	1.16	Sand
6	110	1.67	7.62	0.57	8.12	7.00	239.43	19.73	2.45	2.99	7.62	91.76	3.98	4.25	Sand
7	150	1.23	4.63	0.86	7.39	6.62	114.32	65.18	2.00	0.65	27.84	62.75	36.71	0.55	Sandy loam
8	135	2.49	7.62	0.71	8.20	4.02	164.02	5.23	2.44	1.90	9.46	96.27	2.11	1.62	Sand
9	150	5.15	9.62	0.65	8.15	2.33	26.01	21.64	2.13	1.44	15.17	86.44	11.29	2.27	Loamy sand
10	100	18.56	2.19	0.59	7.93	3.35	175.33	20.16	2.13	2.09	8.07	81.63	15.56	2.82	Loamy sand
11	90	37.83	4.62	0.62	8.18	6.99	236.98	2.94	2.33	1.31	9.37	84.83	12.88	2.29	Loamy sand
12	130	29.08	5.62	0.60	7.64	4.03	224.63	4.99	2.56	1.71	12.59	94.14	2.78	3.08	Sand
13	85	9.79	3.62	0.54	7.62	10.89	268.80	0.92	2.28	2.61	8.02	90.84	3.22	5.94	Sand
14	150	0.00	4.62	0.63	8.53	2.29	53.19	3.53	2.75	1.28	12.71	86.57	11.16	2.27	Sand
15	150	8.54	6.62	0.62	8.00	14.75	120.84	60.63	1.99	2.39	13.69	93.72	3.00	3.28	Sand
16	10	4.72	12.65	0.65	7.50	10.50	42.00	68.25	1.50	1.60	10.40	86.30	11.20	2.50	Loamy sand
17	10	0.50	14.62	0.60	7.72	6.74	147.99	68.24	2.60	1.60	8.90	87.00	10.10	2.90	Sand
18	15	0.36	13.62	0.78	7.50	22.70	164.98	17.34	2.70	0.77	15.70	98.00	0.80	1.20	Sand
19	20	2.43	11.64	0.56	8.12	5.75	208.98	77.41	1.80	1.80	11.60	55.40	42.50	2.10	Sandy loam
20	20	2.03	10.67	0.49	8.25	3.84	116.99	68.11	2.90	6.50	5.80	77.80	10.70	11.50	Sandy loam
21	30	7.47	11.96	0.59	7.89	17.15	123.99	15.65	2.30	0.66	16.70	55.50	43.00	1.50	Sandy loam
22	30	4.36	13.65	0.66	7.85	27.05	61.99	72.20	1.10	1.10	13.40	86.30	11.20	2.50	Loamy sand

EF, erodible fraction; EC, electrical conductivity; OM, organic matter; ESP, exchangeable sodium percentage

Topographic features

Results in Fig. 4 show maps of the topographic features (slope, aspect, SRI and TWI). The slope map (Fig. 4a) shows values varying from 0 to 80%, indicating a flat to very steep gradient. The sloping areas (very gently sloping, gently sloping, sloping and strongly sloping) covered the majority of the studied area (71.41%), while the remaining area was dominated by flat to nearly level gradient (20.42%), and steeply (moderately steep, steep and very steep) gradient (8.17%). These results reveal that sprinkler and drip irrigation rather than surface irrigation are recommended (Albaji et al., 2015).

The aspect map (Fig. 4b) shows that slope facing south direction dominated the studied area (33.34%) followed by west (24.74%) north (22.25%), and flat (10.26%) direction, while the east direction was the least frequent (9.41%).In areas located in northern hemisphere, north-facing slopes are less exposed to sunlight than south-facing ones. Hence, they have a high moisture content that controls the temperature gradient and surface warming (Haghighi et al., 2021).

The SRI expresses the resistance of soil to erosion and ranges from 0 (high roughed) to 1.0 (completely level surface) with values close to 0 being preferred (Fenta et al., 2020). Accordingly, in the current work, the surface resistance was classified into five classes; very highly, highly, moderately, low and very low resistance. These classes correspond to SRI values< 0.2, 0.2 – 0.4, 0.4 – 0.6, 0.6 – 0.8, and > 0.80, respectively (as presented in Table 1). As shown in Fig. 4c, the SRI varied from 0.13 to 0.84, indicating a very high to very low surface resistance. Of the total area, 76.95% was classified as moderately resistant, 15.69% as highly resistant, 7.34% as low resistant, while very high and very low resistant areas did not exceed 0.03%. These findings reflect the high potentiality of agricultural development in the studied area as surface roughness is an effective constrain for soil particles movement due to wind action (Fenta et al., 2020).

The TWI is a measure of the topographic control on soil wetness and higher values indicates the ability of soil to retain water (John et al., 2021). Results in Fig.4d reveal that the TWI in the studied area varied from 3.89 to 14.86, indicating a moderate to very high wetness degree (Sharma and Singh, 2017). Areas of very high wetness degree covered the majority of the studied area (97.79%), while those of high and moderate degrees occupied 2.18 and 0.03%, respectively.

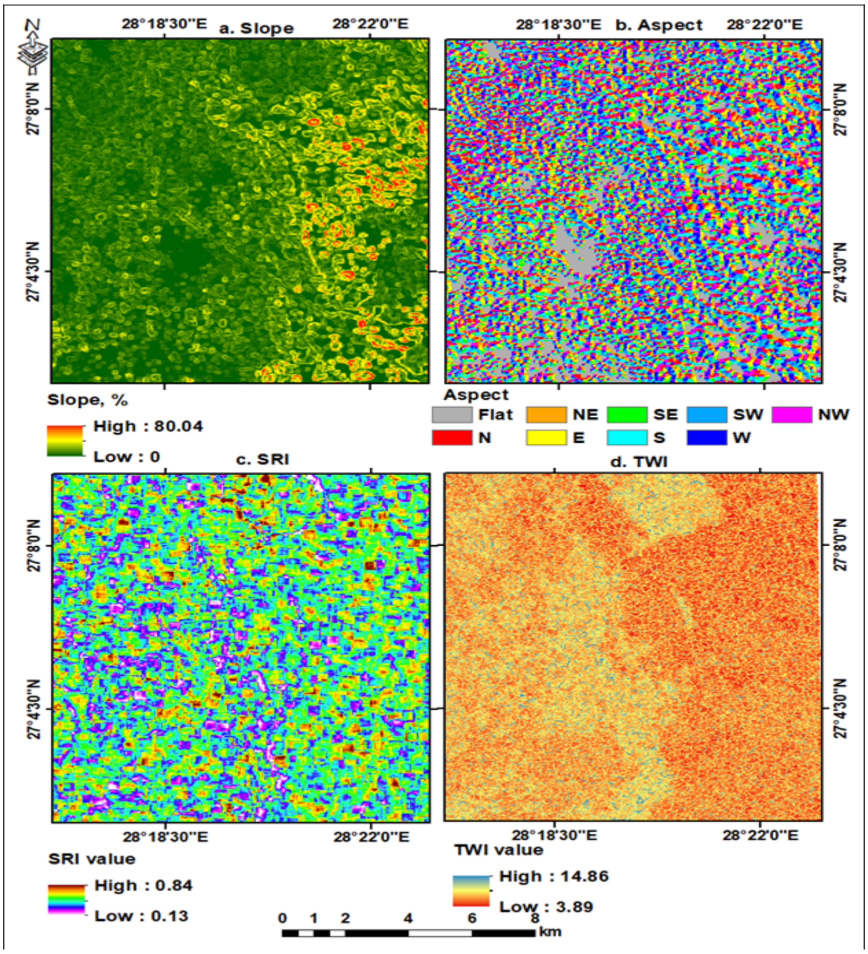

Fig. 4. Maps of topographic features in the studied area

Multivariate statistical analysis

Correlation analysis

Pearson's correlation matrix (Table 5) show that the soil depth showed a highly significant negative correlation ($p < 0.01$) with gravel content, and significant negative correlations($p < 0.05$) with EC and gypsum content. On the other hand, gravel contents showed a significant positive correlation with EC, and a highly significant correlation with gypsum content. These results illustrate that deep soils showed a suitable physicochemical quality regarding rooting development and salinity level. The clay content showed highly significant negative correlations with both ESP and EF. This indicates other soil colloids (Ca/Mg carbonate and Fe-Mn oxides) might play a greater role inNa^+adsorption on soil surfaces than clay minerals.Carbonate minerals and Fe-Mn oxides are more effective adsorbents than clay minerals under aridity conditions (Blume et al., 2016). On the other hand, the presence of clay could produce better aggregation that reduce the detachment of soil particles, and thus decreases the erodible fraction in soils (Guo et al., 2017). The soil pH showed a high significant negative correlation with EC. This might be a result of the presence of neutral salts (NaCl and $MgCl_2$) that inhibit the hydrolysis reaction of Na-saturated surfaces. Furthermore, high CO_2 partial pressures in the soil air reduce pH owing to the formation of HCO_3 in the soil solution (Blume et al., 2016). The ESP showed a highly significant positive correlation with EF. This is because high exchangeable Na^+ on soil surface enhance the dispersion of soils particle (Blume et al., 2016) that in turn increase the soil erodible fraction. The TWI showed highly significant negative correlations with slope, aspect and SRI. This reflect a high contribution of regional terrain complexity on soil moisture content (Haghighi et al., 2021). Results of the correlation analysis demonstrate that PCA/FA would perform well in estimating weights of the selected variable as they linear correlations among each other (Härdle and Simar, 2015).

Principal component analysis

Results show that the Kaiser–Meyer–Olkin (KMO) test value of the standardized data is 0.53 (higher than 0.5) and its Bartlett spherical test value is 0.001 (less than 0.05). This demonstrate that the PCA method was appropriate for dealing with the selected criteria (Mohamed et al., 2020). As shown in Table 6, the first five PCs had eigenvalues higher than 1, and were responsible for 80.63% of the total variance. The PC1 represented 17.70% of the total variance and was dominated by topographic attributes, including slope, aspect and SRI with high positive loadings, and TWI with a high negative loading. This illustrates that low sloping and smooth areas have higher wetness degree than steep sloping and rough areas (Mattivi et al., 2019). The PC2 accounted for 17.47% of the total variance and was dominated by the soil erodible fraction and ESP (with high positive loadings) and clay with a high negative loading. This demonstrates that soil with high ESP and low clay content are more susceptible to erosion hazards (Guo et al., 2017).The PC3 contributed to 16.08% of the total variance, involving gravel and EC with high positive loadings, and depthas well as pH with high negative loadings. These findings reveal that deep soils were characterized by low gravel and soluble saltcontents, but higher pH values than shallow soils.The PC4 mad up 14.94% of the total variance and was dominated by the silt content with a high positive loading and sand content with a high negative loading. This result affirms the different sedimentation regime of the sand and silt particles. The PC5 represented 14.44% of the total variance, including $CaCO_3$ with a high positive loading and gypsum with a high negative loading. This results reflect the different lithogenic source of lime and gypsum in soils.

Assessment of agricultural potentiality

Values of PSI, CSI, TI and ErI of the studied soils units are shown in Table 7, and the spatial distribution of each class is presented in Fig. 5. Results indicate that the PSI ranged from 14 to 70 under sprinkler irrigation and from 23 to 85 under drip irrigation. This indicates that the soils were of very low to highquality under sprinkler irrigation, while very low to very high quality under drip irrigation. The spatial distribution of quality grades shows that under sprinkler irrigation, low-quality soils covered 38% of the studied area, while moderate, high and very low-quality soils occupied about 33, 25 and 1% of the total area, respectively. Under drip irrigation, moderate-quality soils covered 38% of the total area, while very high, high and very low-quality soils covered 25, 33, and 1% of the total area, respectively. Generally, modern irrigation systems are suitable under a wide range of soil texture and depth (Albaji et al., 2010; Albaji et al., 2015), which gave them the superiority under the studied area conditions.

The CSI ranged from38 to 90 under the sprinkler irrigation and from 54 to 90 under drip irrigation. This indicates that the soils were of low to very high quality under sprinkler irrigation, while moderate to very high quality under drip irrigation. Under sprinkler irrigation, the moderate-quality soils covered the majority (78%) of the area, while those of very high, high and low quality occupied 3, 15 and 1% of the total area, respectively. For drip irrigation, soils of high and very high quality covered 89 and 7% of the total area, respectively, while those of moderate quality covered 1% of the total area. Salinity and alkalinity are the most limiting factors in the studied area, which are common in arid environments (El Nahry and Mohamed, 2011).

TABLE 5. Pearson's correlation matrix among the studied parameters

Parameter	Depth	Gravel	Sand	Silt	Clay	pH	EC	ESP	$CaCO_3$	Gypsum	Slope	Aspect	TWI	SRI
Depth	1.00													
Gravel	-0.79**	1.00												
Sand	0.10	-0.05	1.00											
Silt	-0.06	0.04	-0.99**	1.00										
Clay	-0.27	0.04	0.12	-0.27	1.00									
pH	0.32	-0.24	-0.19	0.16	0.15	1.00								
EC	-0.48*	0.48*	0.21	-0.18	-0.10	-0.49*	1.00							
ESP	0.20	0.01	-0.33	0.41	-0.58**	-0.25	0.12	1.00						
$CaCO_3$	0.14	-0.40	0.03	-0.03	0.07	-0.08	-0.15	-0.37	1.00					
Gypsum	-0.52*	0.60**	-0.30	0.26	0.15	-0.21	0.20	0.21	-0.44*	1.00				
Slope	0.09	-0.33	0.07	-0.06	-0.03	-0.01	-0.14	-0.10	0.34	-0.29	1.00			
Aspect	0.09	-0.36	-0.16	0.16	-0.07	0.04	-0.08	-0.03	0.29	-0.38	0.72**	1.00		
TWI	0.16	0.08	0.20	-0.16	-0.19	-0.03	0.11	0.06	-0.04	-0.16	-0.59**	-0.57**	1.00	
SRI	0.05	-0.21	-0.19	0.14	0.23	0.02	-0.29	-0.18	0.14	0.06	0.37	0.41	-0.72**	1.00
EF	0.29	-0.12	0.00	0.11	-0.66**	-0.23	0.05	0.71**	-0.14	0.01	-0.12	-0.02	0.20	-0.03

*Correlation is significant at the 0.05 level.

**Correlation is significant at the 0.01 level.

EC, electrical conductivity; ESP exchangeable sodium percentage; TWI, topographic wetness index; SRI, surface roughness index; EF, erodible fraction.

TABLE 6. Varimax rotated component matrix for the studied parameters

Index	Property	PC1	PC2	PC3	PC4	PC5	Comm	Wi	W_x
	Eigenvalue	3.58	2.82	2.64	1.91	1.15			
	Variance, %	17.70	17.47	16.08	14.94	14.44			
	Cumulative, %	17.70	35.17	51.24	66.18	80.63			
Index	Property	Eigenvectors					Comm	Wi	W_x
Physical	Depth	-0.04	0.39	-0.78	-0.19	0.26	0.88	0.07	0.36
	Gravel	-0.23	-0.19	0.66	0.13	-0.52	0.82	0.07	
	Sand	-0.10	-0.07	0.08	-0.98	0.08	0.98	0.08	
	Silt	0.08	0.19	-0.07	0.97	-0.04	0.99	0.08	
	Clay	0.14	-0.82	-0.06	-0.15	-0.18	0.74	0.06	
Chemical	pH	-0.08	-0.31	-0.71	0.21	-0.05	0.65	0.05	0.31
	EC	-0.15	0.12	0.81	-0.16	-0.02	0.72	0.06	
	ESP	-0.03	0.85	0.06	0.26	-0.24	0.86	0.07	
	$CaCO_3$	0.08	-0.21	0.00	0.05	0.80	0.69	0.06	
	Gypsum	0.05	-0.06	0.36	0.29	-0.75	0.79	0.07	
Topography	Slope	0.72	0.01	0.02	-0.09	0.46	0.74	0.06	0.26
	Aspect	0.71	0.10	-0.03	0.12	0.52	0.79	0.07	
	TWI	-0.92	0.14	-0.04	-0.13	0.10	0.89	0.07	
	SRI	0.81	-0.12	-0.19	0.06	-0.12	0.73	0.06	
Erosion	EF	-0.04	0.89	-0.04	-0.06	-0.10	0.81	0.07	0.07

See footnote of Table 5

Bold face numbers indicate highly-loaded variables

Comm, communality; Wi weight of the property; W_x, weight of the index (sum of W_i)

TABLE 7. Values and ranks of different indices under sprinkler and drip irrigation

Modal Profile	Unit	Irrigation	PSI Value	CSI Value	TI Value	ErI Value
2	Depression	Sprinkler	78	73	85	60
		Drip	67	81	85	60
4	High alluvial terraces	Sprinkler	70	51	69	40
		Drip	85	72	81	40
5	High sand sheets	Sprinkler	50	48	81	40
		Drip	70	69	81	40
7	Moderate alluvial terraces	Sprinkler	70	54	72	40
		Drip	85	77	72	40
9	Low alluvial terraces	Sprinkler	67	48	43	60
		Drip	81	72	51	60
10	Moderately high sand sheets	Sprinkler	67	85	69	60
		Drip	85	85	81	60
13	Moderate sand sheets	Sprinkler	48	65	72	60
		Drip	70	81	85	60
15	Low sand sheets	Sprinkler	48	61	85	60
		Drip	67	69	85	60
17	Low pediplain	Sprinkler	14	90	72	60
		Drip	23	90	72	60
21	High pediplain	Sprinkler	56	38	61	60
		Drip	63	54	72	60
22	Moderate pediplain	Sprinkler	43	51	85	60
		Drip	57	61	85	60

PSI, physical soil index; CSI, chemical soil index; TI, topographic index; ErI, erosion index.

The TI ranged from 43 to 85 under sprinkler irrigation and from 51 to 85 under drip irrigation. This illustrates that the studied area was arranged in quality classes varied form low to very high under sprinkler irrigation, while moderate to very high under drip irrigation. Areas belonged to very high and high-quality classes covered the majority of the studied area, representing nearly 92 under the two irrigation systems. Areas belonged to low and moderate-quality classes dominated only 5% under sprinkler and drip irrigation, respectively. Results of TI, in general, affirm the potentiality of sustainable agriculture in the studied, since topography is a major constrain for irrigated agriculture (Van Ranst and Ann Verdoodt, 2005).

The ErI ranged from 40 to 60, indicting low to moderate quality. The spatial distribution show that around 62% of the total area were classified as moderate-quality, while 35% as low quality.This is attributed mainly to low organic matter and clay contents in the studied soils, which made the soils prone to erosion hazards (Guo et al., 2017).

When combining the four indices, as shown in Fig. 6, the potentiality maps under the two irrigation systems were created (Fig. 7). The proposed model resulted in two potentiality classes, i.e. high and moderate under sprinkler irrigation; meanwhile three classes, i.e. very high, high and moderate under drip irrigation. For sprinkler irrigation, the high potentiality class covered 58.49 km^2, representing 34.82% of the total area. This class included six geomorphic units, i.e. low sand sheets, high alluvial terraces, moderate alluvial terraces, depression, moderately high sand sheets, and moderate sand sheets. The moderate class occupied 104.81 km^2, representing 62.39% of the total area. This class included five units; pediplain (high, moderate and low), low alluvial terraces and high sand sheets.

Under drip irrigation, the very high potentiality class covered 3.67 km^2, making up 2.18% of the total area. This class included one unit, i.e. moderately high sand sheets. The high potentiality class occupied 157.58 km^2, representing 93.81% of the total area. This class involved nine units; pediplain (high and moderate), alluvial terraces (high, moderate and low), sand sheets (moderately high, moderate and low), and depression. The moderate potentiality class covered 2.06 km^2, representing 1.23% of the total area. This class included one unit; low pediplain.

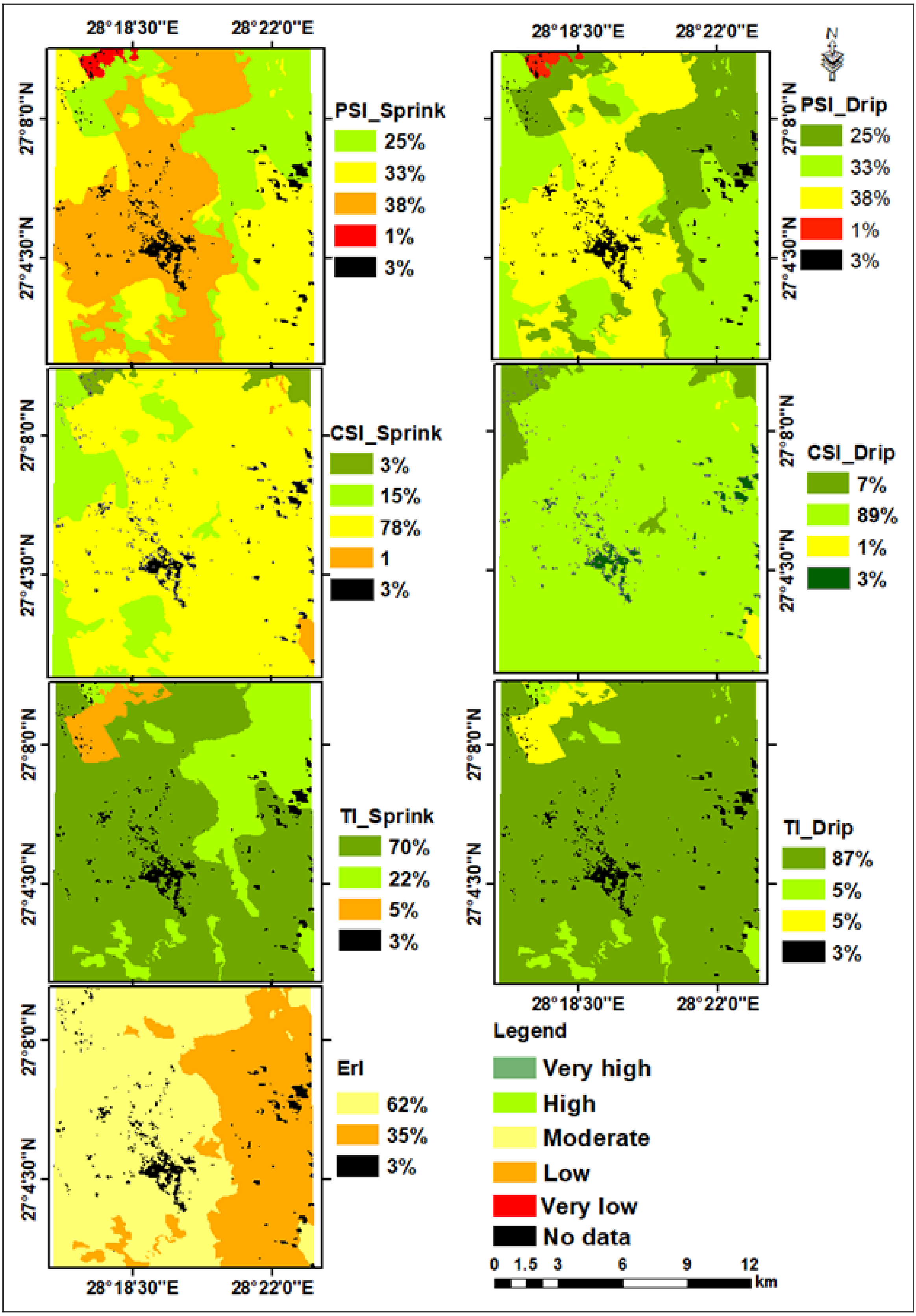

Fig. 5. Maps of potentiality indices of the studied area

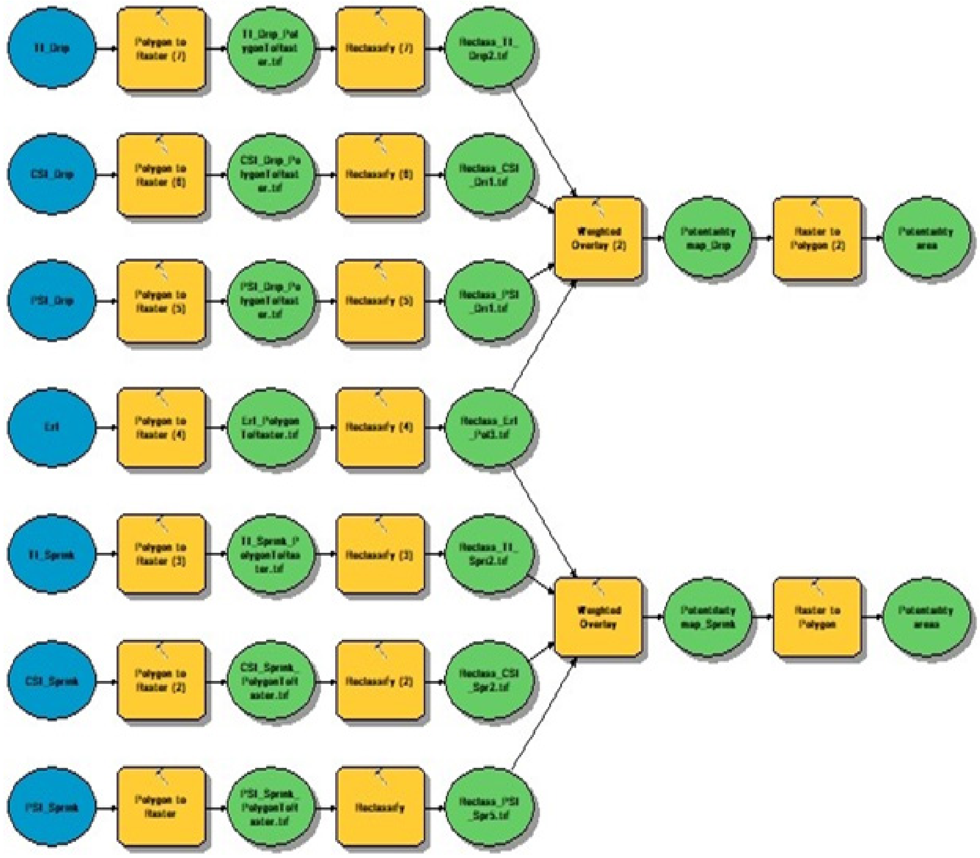

Fig. 6. Flowchart of the designed potentiality model

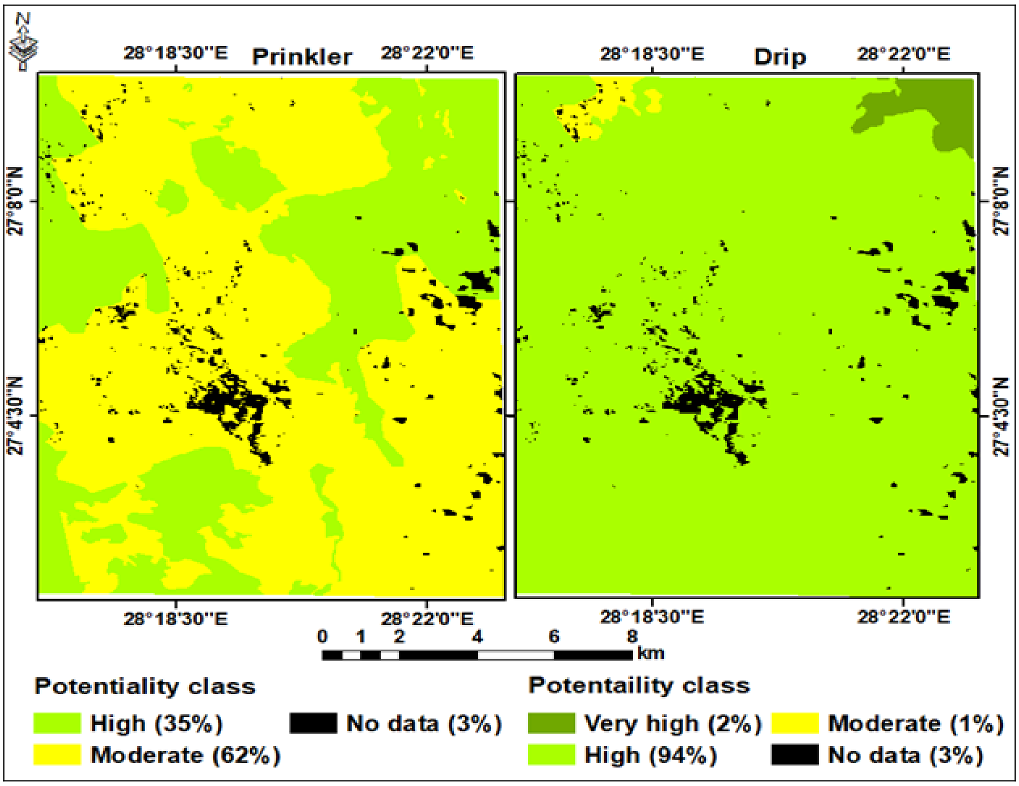

Fig. 7. Potentiality maps of the studied area

Conclusions

Combined useof multivariate analysis and spatial modeling can enhance the insight into the precise assessment of agricultural potentiality in the newly reclaimed desert areas in Egypt. Groundwater quality in the studied area would be highly suitable for different kinds of irrigated agriculture. Soil properties and soil-environmental covariates showed linear correlations among each other. This provided a science-based estimation of parameters weights derived from PCA/FA. These weights reveal that the most effective factors were physical soil properties (0.36), followed by chemical properties (0.31) and topographic features (0.26), while erosion hazards were the least one (0.07).Using the weighted overlay analysis under GIS environment, the four factors were overlain in single maps representing agricultural potentiality under sprinkler and drip irrigation systems. The studied area was classified as moderately (62%) and highly potential (35%) under sprinkler irrigation, while as moderately (1%), highly (94%) and very highly potential (2%) under drip irrigation.The proposed model would provide a useful tool for mapping and monitoring spatial and temporal variations in natural resources in the studied area.

Ethics approval and consent to participate

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

All authors declare their consent for publication.

Contribution of authors

This study was designed and implemented by all the authors, where all contributed to writing the manuscript, interpreting information presented and have read and agreed to the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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تكامل التحليل المتعدد المتغيرات والنمذجة المكانية لتقييم إمكانية الزراعة في واحة الفرافرة – صحراء مصر الغربية

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تهدف هذه الدراسة إلى إستخدام التحليل الإحصائي المتعدد المتغيرات والنمذجة المكانية في تقييم إمكانية الزراعة في واحة الفرافرة بصحراء مصر الغربية. تم تمثيل الوحدات الجيومورفولوجية بمنطقة الدراسة بعدد ٢٢ قطاع أرضي جمعت منها عينات التربة وتم تحليلها كيميائياً وفيزيائياً. تم تجميع ١٠ عينات مياه من الآبار الجوفية بالمنطقة وتحليلها. كما تم إستخلاص بيانات التضاريس من نموذج الإرتفاعات الرقمية. أوضحت الدراسة أن المياه الجوفية ذات نوعية ممتازة لكافة أنواع الري الحقلي. أكدت نتائج تحليل الإرتباط وجود علاقات خطية بين خواص التربة وعناصر التضاريس المختلفة. أوضحت نتائج التحليل العاملي وتحليل المكونات الرئيسية أن أكثر العناصر تأثيراً على إمكانية الزراعة في المنطقة هي الخواص الطبيعية للتربة، الخواص الكيميائية للتربة، التضاريس، وأخيراً مخاطر النحر. أظهرت نتائج النموذج المكاني أن حوالي ٨٠٪ من منطقة الدراسة تعتبر ذات إمكانية متوسطة، بينما ١٦٪ ذات إمكتنية عالية تحت نظام الري بالرش. تحت نظام الري بالتنقيط وجد أن ١٦٪ من المنطقة ذات إمكانية عالية جداً، ٥٩٪ ذات إمكانية عالية، بينما ٢١٪ ذات إمكانية متوسطة.