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Mapping and evaluating land suitability using a GIS-based model

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ABSTRACT

Wheat is considered the most important crop in Egypt; however, not all of the land in Egypt is equally suitable for growing wheat. The main objective of this study was to develop a spatial model for land suitability assessment for wheat crop integrated with geographic information system (GIS) techniques. Organic matter, N, P, K, Zn, drainage, texture, depth, topography, surface stoniness, hard pan, hydraulic conductivity, water holding capacity, salinity, ESP, $CaCO_3$ and pH were recognized as factors affecting land suitability for wheat crop in the study area. Three thematic indicators were used in assessing land suitability, soil fertility, chemical and physical properties quality indices. The results of the proposed model were compared with the Square root and Storie methods. The results from the proposed model showed that most of the units fall within the highly suitable class and the moderately suitable class which together represent 71.44% of the total area. About 29% of the study area was marginally suitable and unsuitable for wheat crop and those areas correspond to the adverse physical and chemical properties of the soil. The comparison of the results of the three approaches used showed that the present model has a high level of agreement with the Square root method, whereas all land units have the same classes of suitability with the exception of one unit. The present model allows obtaining results that seems to be corresponded with the current conditions in the area.

1. Introduction

Agriculture is one of the largest sectors of the Egyptian economy and provides 20% of gross domestic product, 34% of the total exports and employs 32% of the total labor force (CAPMAS, 2012). Land resources in Egypt face pressures from continuing land degradation and increasing number of people. The population in Egypt is growing very rapidly as its density has doubled during the last three decades (Hamza and Mason, 2004). Therefore, the efficient management of natural resources in Egypt is essential for ensuring food supplies and sustainability in agricultural development.

In order to manage land resources properly, land suitability assessment is often conducted to determine which type of land use is most appropriate for a particular location (Bodaghabadi et al., 2015). Land suitability analysis is a method of land evaluation, which allows identifying the main limiting factors of a particular crop production (Halder, 2013). At the same time it enables decision makers to develop a crop management system for increasing land productivity (Chen, 2014). Land suitability assessment is a planning approach to avoid environmental conflicts by the segregation of competing land uses (FAO, 1976; Rossiter, 1990; FAO, 1991; Al-Mashreki et al., 2011; Ashraf and Normohammadan, 2011). Land suitability evaluation can be either qualitative or quantitative. Qualitative approach is used to assess land potential on a broad scale and the results are given in qualitative terms. Quantitative approach involves more detailed land attributes by using parametric techniques which allow various statistical analyses to be performed. The land suitability evaluation procedure in the quantitative approaches involves many simulation modeling systems (Van de Graaff, 1988; Shields et al., 1996) to quantify the potential of land for specific uses. FAO guidelines on land evaluation system (FAO, 1976 &1985) and physical land evaluation methods (Sys et al., 1991) were widely used for land suitability assessment.

Remote sensing and Geographic Information Systems (GIS) hold great promises for improving the convenience and accuracy of spatial data, more productive analysis and improved data access. These technologies have been used to assess the criteria required to define the suitability of land (Booty et al., 2001; De la Rosa and Van Diepen, 2002; Darwish et al., 2006; Mokarram et al., 2010; El Baroudy, 2011; Hamzeh et al., 2014; Mishelia and Zirra, 2015) and were also adopted for the present study.

In Egypt, the main field crops are maize, rice and cotton during the summer season and wheat, clover and bean during the winter season. Cereal production represents about 50% of the value of field crops, occupying about 2.72 million ha of the whole cropped area. Wheat occupies approximately 1.26, maize 0.88, rice 0.59, sorghum 0.15 and barley 0.19 million ha (FAO, 2005). Wheat is considered the most important crop and the Egyptian Government gives priority to wheat production providing farmers with varieties which tolerate different types of stress. The main objective of this research is to prepare land suitability

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evaluation maps for wheat crop using a GIS-based and to compare it with Square root and Storie methods for areas in the northern part of the Nile Delta.

2. Materials and methods

2.1. Description of the study area

The study area is a coastal region adjacent to El-Manzala Lake in the northern part of the Nile delta. The geographical location is in UTM zone 36 (30° 58′ 30″–31° 31′ 20″ N; 31° 16′ 20″–32° 12′ 15″ E) covering 4190 km^2 (Fig. 1). The soil temperature regime of the studied area is "Thermic" and the soil moisture regime as "Torric" according to the US Soil Taxonomy System (USDA, 2010). The study area is characterized by a Mediterranean climate with a little rain in winter and a hot arid in summer. The amount of annual rainfall is very low and mostly falls in winter. The maximum rainfall is recorded in January, reaching about 40 mm in Damietta station. Temperatures are high during the summer months and relatively low in winter. The hottest temperature is recorded in August, reaching about 31 °C and the coldest month is January, reaching about 18 °C. Potential evaporation is low (3.2 mm/day) in December and January when the temperature is comparatively low. Potential evaporation values are high (5.4 mm/day) between June–September when the temperature is comparatively high. The area was formed in the latter part of the Miocene and the beginning of Pliocene periods and the surface of the area is essentially occupied by formations form the Quaternary and Holocene (Said, 1993). The main cultivated crops in the studied area are cotton, rice, corn, clover, barley and beans, meanwhile the common cultivated orchards are citrus, guava, banana, and date palm trees. Vegetables represent small-scattered areas including tomatoes, eggplant, potatoes, watermelon and others (Belal, 2001).

2.2. Digital image processing and physiographic map

Digital image processing for Landsat ETM + satellite image (path 176, row 38) with a spatial resolution of 30 m acquired during 2013 was performed using ENVI 5.1 software. The original scan line corrector (SLC-off) image has been replaced with estimated values based on histogram-matched scenes to improve the utility of the SLC-off data. According to Lillesand and Kiefer (1979), the image was stretched using linear 2%, smoothly filtered, and their histograms were matched. Image was atmospherically corrected using FLAASH module (ITT, 2009). The ETM + image was geometrically corrected using a rectification method (image to map). Two topographic maps with scale of 1:50,000 (Egyptian General Survey Authority) were digitized and converted to DXF format and the coverage was topologically processed in UTM projection, Zone 36 and WGS-84 datum. Elevation contour lines and points were used to generate raster Digital Elevation Model (DEM) (10 × 10 m) using Arc-GIS 10.1 software. The physiographic units were defined from the satellite image and DEM, classified into groups and the map legend was established according to Zinck and Valenzuela (1990).

2.3. Fieldwork and laboratory analyses

Field studies and ground truth were carried out to identify the physiographic units and to examine the reality of the interpretation. A total of 90 observation points were taken to check the accuracy of mapping units. Twenty seven soil profiles were taken from the different physiographic units. A detailed morphological description of the studied soil profiles was elaborated on the basis outlined by FAO (2006). Representative 103 soil samples have been collected from the soil profiles and analyzed for physical and chemical characteristics using the standard analytical methods as described below.

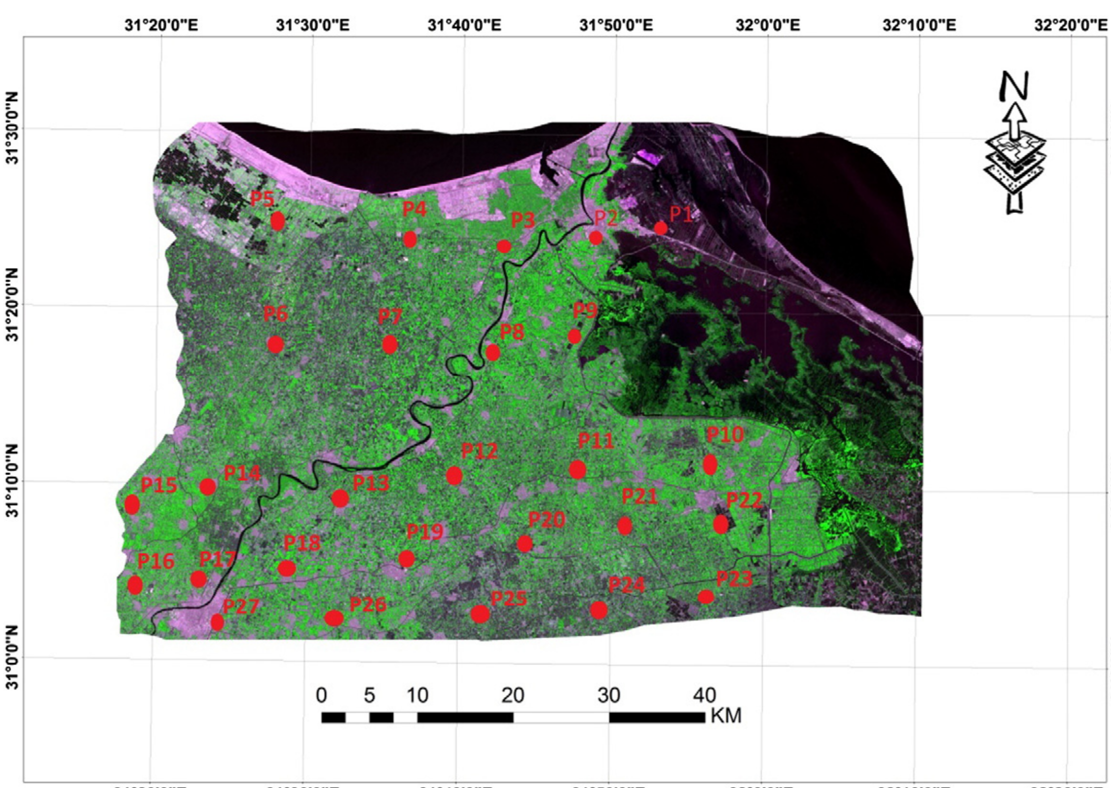

Fig. 1. Location of the study area and soil profiles.

Table 1
Factor score of land quality parameters for wheat crop in the study area.
Source: FAO, 1976 and Sys et al., 1993.

Land quality parameter	Factor score					
	Diagnostic factor	Unit	1	0.8	0.5	0.2
Soil fertility						
	N	mg/kg	>80	80–40	40–20	<20
	P	mg/kg	>15	15–10	10–5	<5
	K	mg/kg	>400	400–200	200–100	<100
	Organic matter	g/100 g	>2	1–2	0.5–1	<0.5
	Zn	mg/kg	>1	1–0.5	0.5–0.25	<0.25
Physical properties						
Drainage (R)		–	Well	Moderate	Poor	Very poor
Texture (T)		g/100 g	L, SCL, SL, LS, CL	SC, SiL, SiCL	Si, C, SiC	G, S
Depth (D)		cm	>100	100–50	50–25	<25
Topography (F)	Slope	g/100 g	<2	2–4	4–6	>6
Surface stoniness(Y)	>2 mm	g/100 g	<20	20–35	35–55	>55
Hard pan (P)		cm	>100	100–50	50–20	<20
Hydraulic conductivity (G)		cm h-1	<0.5	0.5–2	2–6.25	>6.25
Water holding capacity(WHC)		g/100 g	>50	50–20	20–15	<15
Chemical properties						
Salinity hazard (S)		dS m^{-1}	<4	4–8	8–16	>16
ESP		g/100 g	<10	10–15	15–20	>20
$CaCO_3$ content(K)		g/100 g	<5	5–10	10–15	>15
Soil reaction (H)	pH	–	5.5–7	7–7.8	7.9–8.5	>8.5

2.3.1. Analysis of physical properties

Soil color in both wet and dry samples was determined with the aid of Munssel Color Charts, C.U.S.D.A. Particle size distribution of the soil samples was determined according to the international pipette method (Gee and Bauder, 1986). Soil bulk density was determined from the volume–mass relationship for each core sample according to Blake and Hartge (1986). Soil hydraulic conductivity was determined at saturation under a constant head (Klute and Dirksen, 1986).

2.3.2. Analysis of chemical properties

Soil samples have been collected from each horizons of the soil profile and were air dried and the less than 2 mm particles were used for chemical analyses. Electrical conductivity (EC) was determined in extracted saturated soil paste, soil reaction (pH) was determined in (1: 2.5) soil water suspension according to Page et al. (1982). Organic matter content (OM) was determined by the modified Walkley and Black method as described by Jackson (1973).

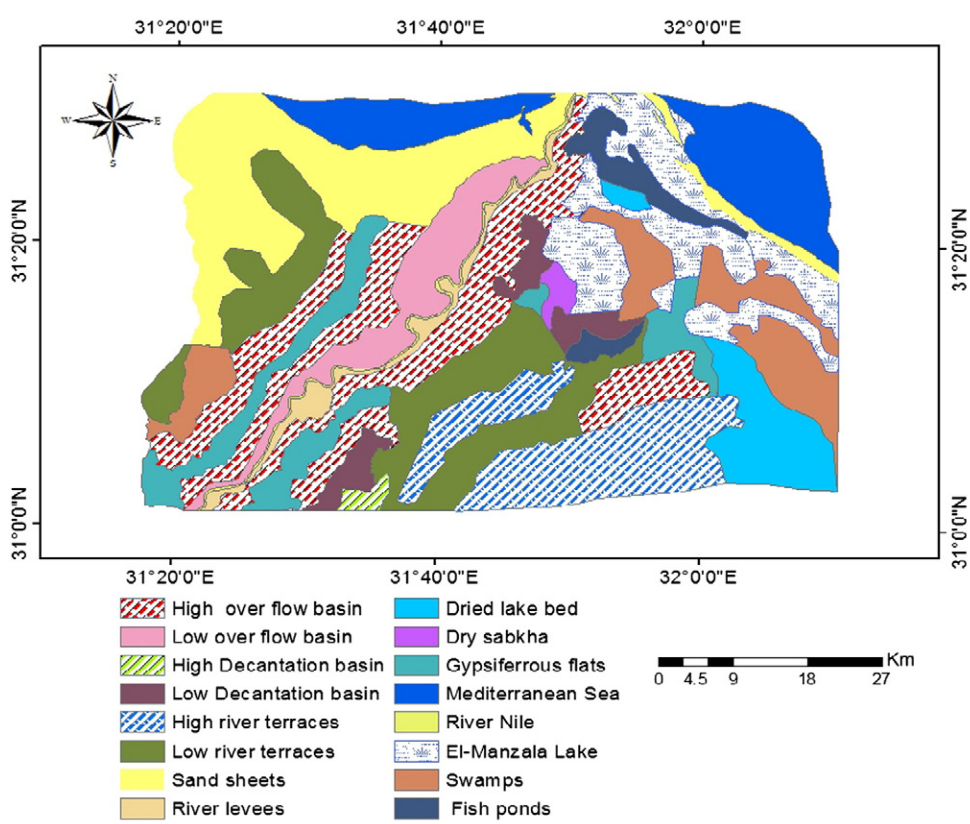

Fig. 2. Physiographic map of the study area.

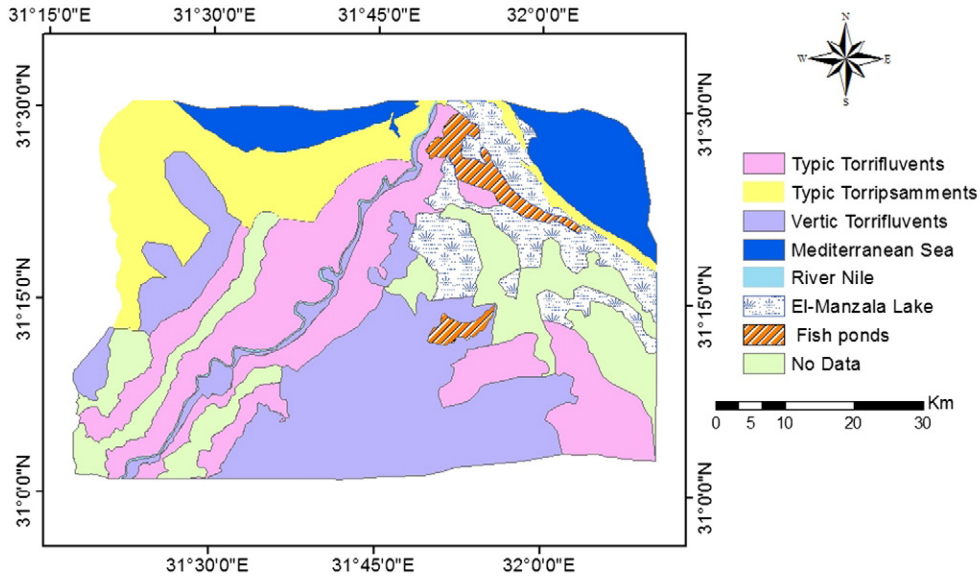

Fig. 3. Soil map of the study area.

Exchangeable sodium percentage (ESP) was determined by Ammonium acetate (NH4OAC) according to the method developed by Lavkulich (1981) and determined using flamephotometer as reported by Page et al. (1982). Total calcium carbonate was determined volumetrically using Collin's calcimeter (Loeppert and Suarez, 1996). Available nitrogen in the soil was extracted in the 2.0 M KCl and determined by micro-Kjeldahl apparatus. Available phosphorus was extracted in 0.5 N $NaHCO_3$ solution (pH 8.5) and determined using spectrophotometer. Available potassium was extracted in the 1.0 N ammonium acetate solution (pH 7) and determined using flame photometer. Available nitrogen, phosphorus and potassium were determined according to Jackson (1967) and Page et al. (1982). Available Zn was extracted by using DTPA and determined by Atomic Absorption (Lindsay and Norvell, 1978). The soils were classified to the sub great groups level based on the American Soil Taxonomy (USDA, 2010). Then the physiographic and taxonomic units were correlated in order to identify the major soil sets of the studied area (Elberson and Catalan, 1987).

2.4. Land suitability assessment

Land suitability analysis is a method of land evaluation which measures the degree of appropriateness of land for a certain use. The present study is a qualitative and quantitative evaluation of land to determine land suitability for wheat crop in the study area. The selection of influencing factors was based on the growth requirement of the wheat crop according to Sys et al., 1993. Eighteen parameters have been used in this work to study land suitability for wheat. These parameters are organic matter, N, P, K, Zn, drainage, texture, depth, topography, surface stoniness, hard pan, hydraulic conductivity, water holding capacity, salinity, ESP, $CaCO_3$ and pH.

Three thematic indicators were used in assessing land suitability: soil fertility, chemical and physical quality indices. The following equation was used to calculate land suitability using GIS spatial model:

$$LS = (FQIC \times QI \times PQI)^{1/3},$$

where LS is the land suitability factor, FQI is a fertility quality index, CQI is a soil chemical quality index and PQI is a soil physical quality index.

The fertility quality index was calculated using the following formula:

$$FQI = (S_N \times S_P \times S_K \times S_{zn} \times S_{OM})^{1/5},$$

where the S_N, S_P, S_K, S_{zn} and S_{OM} are parameters that express factors for, respectively the available nitrogen, the available phosphorous, available potassium, available zinc and organic matter content. The rating for these factors is explained below.

The chemical quality index was calculated using the following formula:

$$CQI = (S_S \times S_E \times S_C \times S_H)^{1/4},$$

where the S_S, S_E, S_C and S_H are parameters that express factors for, respectively the soil salinity, the exchangeable sodium percent, the $CaCO_3$ content and the soil pH.

The physical quality index was calculated using the following formula:

$$PQI = (S_R \times S_T \times S_D \times S_F \times S_Y \times S_P \times S_G \times S_W)^{1/8},$$

where the S_R, S_T ,S_D ,S_F ,S_Y ,S_P ,S_G and S_W are parameters that express factors for, respectively the drainage, the texture, the soil depth, the topology, the surface stoniness, the hard pan depth, the hydraulic conductivity and the water holding capacity.

Rating is an evaluation, usually expressed in numerical terms, of how suitable a site is supporting a specific land use and there is no uniform standard for rating factors. The parameters or factors were rated based on experts' suggestions and a review of literature (FAO 1976 & 1985; Sys et al., 1991 & 1993; Rezaei et al., 2006; Maleki et al., 2010; Ashraf et al., 2010; Mustafa et al., 2011; Halder, 2013; Chen, 2014). In this study, rates were assigned to the elements of a particular parameter with valid scores ranging from 0.2, the worst conditions, to 1, the best conditions (Table 1).

Each class was given a weighted index according to the importance of its role in land suitability for crop production. A value of 0 was assigned to unclassified areas. The suitability ratings were then divided into four classes (S1: highly suitable, S2: moderately suitable, S3: marginally suitable and N: unsuitable). The results of the proposed model were then compared with two classical parametric methods; the Square root and Storie methods.

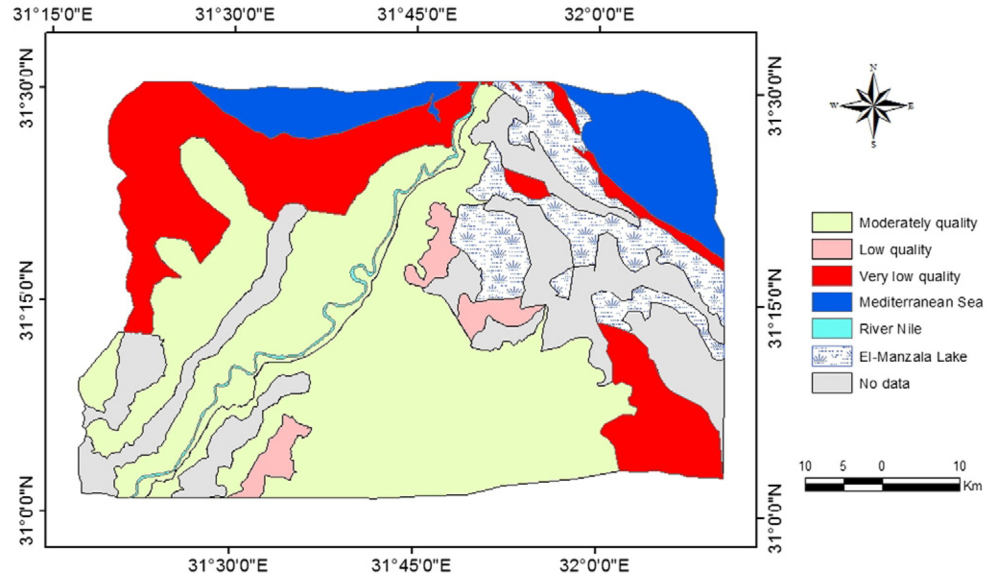

Fig. 4. Fertility quality classes of the study area.

Storie method is used for calculating the land index (I) following equation:

$$I = A \times B/100 \times C/100 \times D/100 \times \ldots$$

where, I is the suitability index, A is the rating of surface texture parameter and B, C, D are the rating values for other parameters. A score ranging from 0 to 100% is determined for each factor, and the scores are then multiplied together to generate an index rating (Storie, 1978).

The Square root method uses the following formula to calculate soil suitability:

$$I = R\min\sqrt{\frac{A}{100} \times \frac{B}{100} \times \frac{C}{100} \times \ldots}$$

where I is the square root index, R_{min} is the minimum rating and A, B, C,… are the remaining rating values (Khiddir, 1986).

To assess the agreement between the initial model and both the Square root and Storie methods, the Kappa statistic developed by Cohen (1960) was used. Kappa coefficient was used to assess the agreement between alternative methods of categorical assessment. The calculation is based on the difference between how much agreement is actually present compared to how much agreement would be expected to be present by chance alone. The Kappa coefficient was calculated using the following formula:

$$K = \frac{P(A) + P(E)}{1 - P(E)}$$

where K is the Kappa coefficient, P(A) is the proportion of times that the coders agree and P(E) is the proportion of times that we would expect them to agree by chance. A Kappa value of 0 indicates that there is a poor agreement between the methods and a value of 1 indicates an almost perfect agreement.

3. Results and discussion

3.1. Physiographic map and soils of the study area

Based on a Landsat ETM+ image, the digital elevation model (DEM) and a field check, the physiography of the studied area has been identified. The obtained results reveal that the main landscapes in the study area are marine, lacustrine and alluvial plains (Fig. 2). The marine plain occupies an area of 582.35 km^2 in the northern part of the zone, as represented by the landform of sand sheets. The lacustrine plain dominates the middle parts of the area; covering 694.46 km^2. It was formed from the interaction between the River Nile and the El-Manzala Lake deposits during flooding. The included landforms in this landscape are swamps (313.81 km^2), Gypsiferous flats (258.16 km^2), dried lake beds (187.98 km^2), fish ponds (100.54 km^2) and dry sabkha (21.95 km^2). The alluvial plain is the main landscape in the study area and dominates the southern parts of the studied area, covering 1927.86 km^2. This landscape resulted from the Nile deposits during the flooding periods before the construction of Aswan dam. The different landforms of the alluvial plain are high overflow basins, low river terraces, high river terraces, low overflow basins, low decantation basins, river levees and high decantation basins with areas of about 620.1, 507.26, 398.36, 205.95, 106.0, 73.5 and 16.69 km^2, respectively. Results indicated that the main soil sub great soil groups in the study area (Fig. 3) are Vertic Torrifluvents, Typic Torrifluvents and Typic Torripssaments and represent 61.90%, 24.20% and 13.90% of the total area, respectively.

3.2. Land suitability

The proposed model was used in assessing land suitability in the study area, using the three indicators, soil fertility, chemical and physical quality indices as described below.

Table 2
Fertility quality classes of the study area.

FQI class	Score	Area (km^2)	Area (%)
High quality	>0.9	0	0
Moderate quality	0.9–0.7	1821.6	67.51
Low quality	0.7–0.5	106	3.93
Very low quality	<0.5	770.4	28.56

Table 3
Soil physical quality (PQI) classes of the study area.

PQI	Class	Score	Area (km^2)	Area (%)
High quality	S1	>0.75	2115.6	78.42
Moderate quality	S2	0.75–0.50	0	0
Low quality	S3	0.50–0.25	582.4	21.58
Very low quality	N	<0.25	0	0

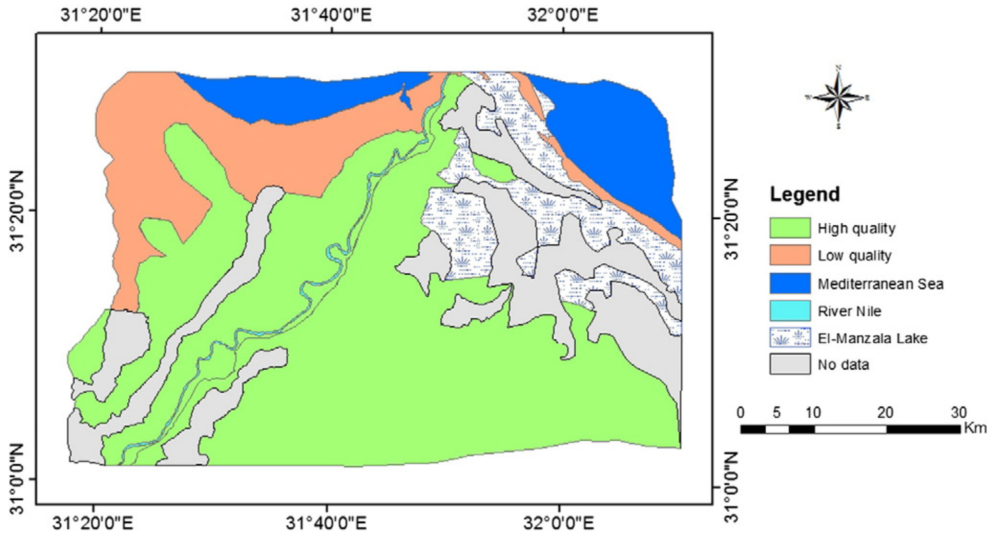

Fig. 5. Soil physical quality (PQI) classes of the study area.

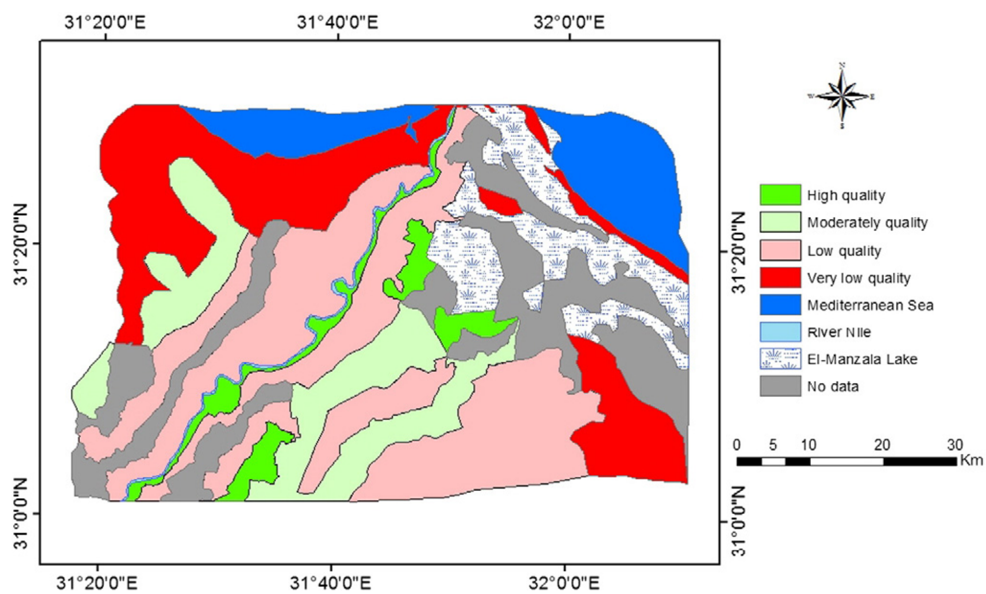

Fig. 6. Soil chemical quality (CQI) classes of the study area.

3.3. Soil fertility quality index (FQI)

The data given in Fig. 4 and Table 2 indicate that FQI in the study area is moderately, low and very low. These qualities represent 67.51%, 3.93% and 28.56% of the total area, respectively. The low quality class occurred in the low decantation basin due to decreased organic matter content, available nitrogen and available potassium. The sand sheets and dried lake bed units have very low quality classes: these soils suffer from deficit of organic matter and also macro and micro elements.

Table 4
Soil chemical quality (CQI) classes of the study area.

CQI class	Score	Area (km^2)	Area (%)
High quality	>0.9	179.5	6.65
Moderate quality	0.9–0.7	523.95	19.42
Low quality	0.7–0.5	1224.41	45.38
Very low quality	<0.5	770.33	28.55

3.4. Soil physical quality index (PQI)

The growth of different crop depends on the soil physical conditions which are needed for good root growth (El Baroudy et al., 2014). Results of PQI indicated that 78.42% and 21.58% of the area were high and low quality, respectively as shown in Fig. 5 and Table 3. The lowest PQI occurred in sand sheet units, those values being a result of adverse saturated hydraulic conductivity and water holding capacity in addition to the coarse texture soil.

3.5. Soil chemical quality index (CQI)

Soil chemical properties affected plant growth, some productivity and yield parameters of crop (OSSOM and Rhykerd, 2007; Eugène et al., 2010). The data given in Fig. 6 and Table 4 indicate that CQI in the El-Manzala area are as follows; 6.65% is high quality, 19.42% is moderate quality and 45.38% is low quality. About 28.55% of the study area is

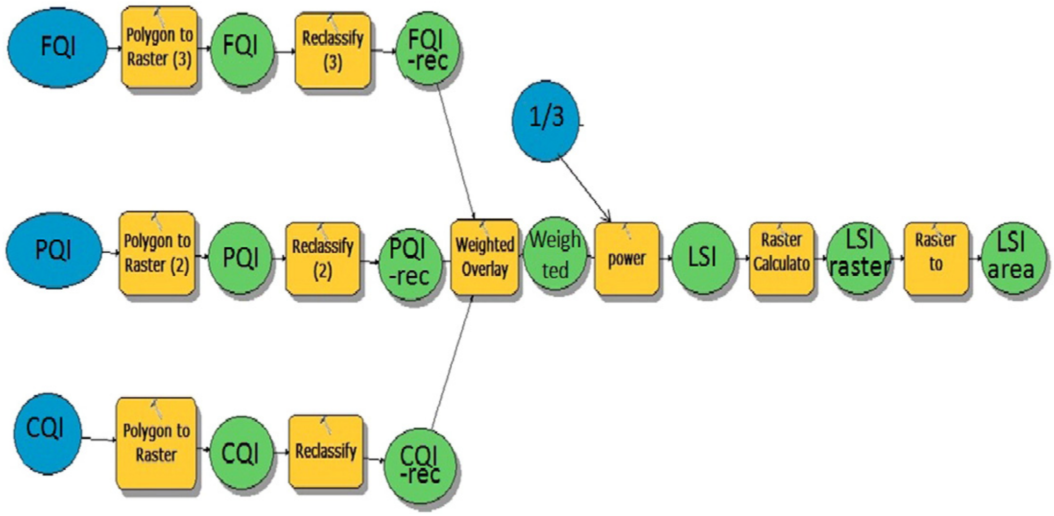

Fig. 7. Flowchart of the designed land suitability modeling.

classified as very low quality, due to some limiting factors such as high salinity, high exchangeable sodium percentage and high pH.

3.6. Land suitability evaluation

In order to identify a land suitability class the following steps were under taken: (1) the features of physical soil properties, chemical soil properties and soil fertility quality indices were transformed into raster layers; (2) raster layers were classified according to the schemes given above (Tables 1 to 4); (3) they were weighted and overlaid; (4) each cell in the resulting raster layer was reclassified into a land suitability class according to Table 5 and, (5) the final resulting raster could be assessed and displayed as a land suitability map (Fig. 7).

The results of the proposed model as shown in Fig. 8 and Table 5 indicate that most units fall under the highly suitable class (S1) and the moderately suitable class (S2) which represents 71.44% of the total area. About 28.56% of the study area in the sand sheets and dried lake beds units was marginally suitable (S3) and unsuitable (N) for wheat and those areas have adverse physical and chemical properties of the soil. The results of the Square root method show that 26.07% of the soils are highly suitable (S1 class), 45.37% are moderately suitable (S2 class), 6.97% are marginally suitable (S3 class) and 21.58% are not suitable (class N). In comparison, the results of the proposed model show that 7.27% of the soils are highly suitable (S1 class), 64.17% moderately suitable (S2 class), 6.97% marginally suitable (S3 class) and 21.58% are not suitable (class N), which are slightly different in comparison with the results of the Square root method. The results of the Storie method show that 26.07% of the soils are highly suitable (S1 class), 7.63% are moderately suitable (S2 class), 44.71% are marginally suitable (S3 class) and 21.58% are not suitable (class N).

When comparing the results of land suitability classification given by the proposed model and the Square root method all units have the same classes of suitability with the exception of soils in the low overflow basins which are in the moderately suitability class (S2) in the Square root method but in the highly suitable class (S1) in the proposed model. With regard to land suitability classification for wheat using the Storie method, most of the soil units in the study area have the same classes of suitability compared with the proposed model except soils in the high overflow basin, low overflow basin and high river terraces. Those units fall under suitability classes S3, S2 and S3, while in the proposed model the fall under suitability classes S2, S1 and S2 respectively (Fig. 9 shows the results of this comparison as a map). Furthermore, the results indicated that suitability index values of the Square root gives were higher than

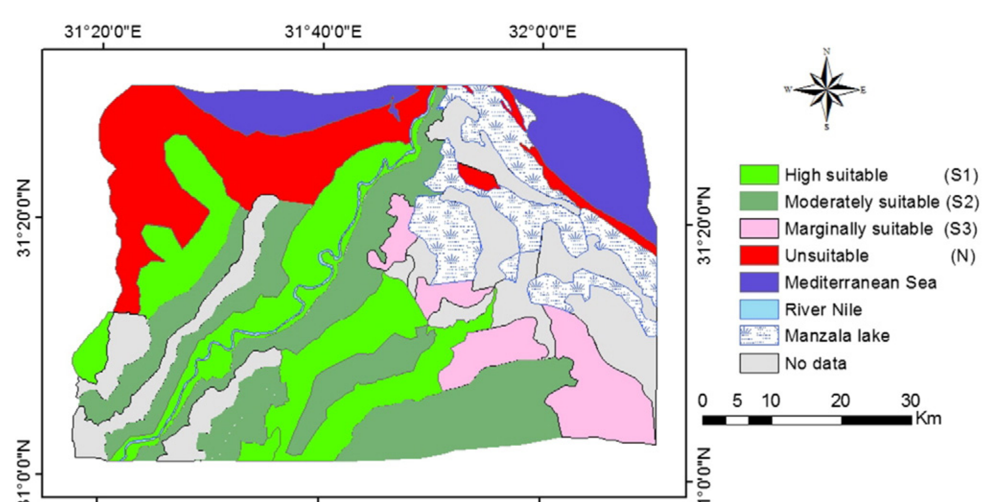

Fig. 8. Suitability map of the study area.

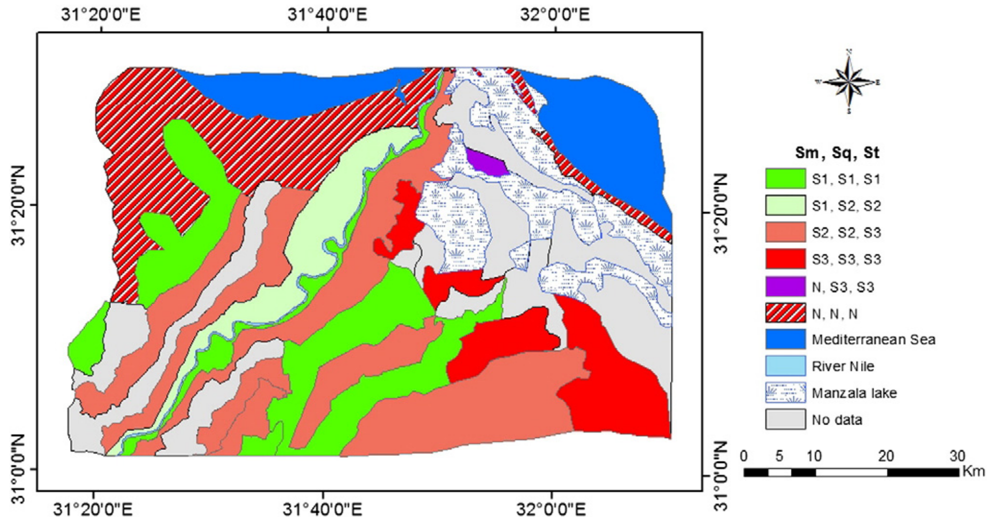

Fig. 9. Comparison between land suitability evaluation by the proposed model (Sm) and both the Square root (Sq) and Storie (St) methods.

Table 5
Land suitability evaluation for wheat crop in the study area.

Suitability	Suitability class	Index value	Area (km^2)	Area (%)
Highly suitable	S1	1–0.8	196.19	7.27
Moderately suitable	S2	0.8–0.6	1731.41	64.17
Marginally suitable	S3	0.6–0.4	188.00	6.97
Unsuitable	N	<0.4	582.40	21.59

that of the Storie method in all the land units in the study area. These results agreed with those obtained by Vargahan et al. (2011); Ashraf and Normohammadan (2011).

The coefficient of Kappa was used for comparing results of the proposed model and both of Square root and Storie methods to assess the level of agreement between the proposed model and parametric methods. The Kappa coefficient is 0.83 between the proposed model and the Square root methods. This value indicates a very good level of agreement between the two methods, while the Kappa coefficient is calculated to be 0.51 between the proposed model and the Storie method which shows a moderate agreement between the two methods for land suitability in the study area.

4. Conclusion

Most land units in the study area fall under the high suitable class and the moderately suitable class for wheat crop production. GIS is a valuable tool to store, retrieve and manipulate the huge amount of data needed to compute and map different quality indices for land suitability. The results of the proposed model are slightly different when compared to the results of the Square root and Storie methods, but they have a high level of agreement with the Square root method, under both of these methods all land units have the same classes of suitability with the exception of one unit. The results of the proposed model agreed with current conditions in the area. The Soil maps for agricultural suitability designed in this research could be helpful in management decisions.

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