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GIS application to identify the potential for certain irrigated agriculture uses on some soils in Western Desert, Egypt

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KEYWORDS
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Abstract The study area lies to the western side of the Nile Delta in El Behira Governorate, with latitudes of 30°30′–30°45′N and longitudes of 29°45′–30°00′E, covering about 670,881 km^2. Landsat ETM^+ image (path 177-raw 39), DEM map and data verification by in situ observations aided by GPS were used for delineating the main physiographic units. The main physiographic units in the study area are: plain, pediplain, terraces, foot slope and table land. Forty-four soil profiles were allocated, exposed and morphologically described to represent the main physiographic units. A total of one hundred and one soil samples were collected from the profiles of the study area for laboratory analyses. The soil suitability maps are produced for three land utilization types of irrigation (LUTs): surface irrigation (LUT1), drip-irrigated vegetables (LUT2) and drip-irrigated trees (LUT3).

The considered land suitability criteria for the aforementioned LUTs are: slope gradient, soil depth, soil erosion, soil drainage, soil infiltration rate, available water holding capacity (AWHC), surface stoniness (gravel, stones and boulders), stones in surface horizon, rock outcrop, soil salinity (EC), exchangeable sodium percent (ESP) and calcium carbonate content. The suitability maps for each of the above criteria and the final land suitability maps of the study area for different LUTs were developed by multiplying the reclassified factors map and adding them by Raster calculator technique in spatial analyst module of Arc GIS 9.3 software. The values which are obtained from the result are classified into three classes. These classes were converted to suitability classes: mod-

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erately suitable (S2), marginally suitable (S3), and not suitable (NS). The most soil limiting factors in the study area for LUT1 are soil depth and drainage followed by slope gradient, salinity and AWHC. However, the most limiting factors for LUT2 and 3 are surface stones and soil depth followed by stone content of surface horizon and soil salinity. Land improvements are required to improve or reduce the severity of limitations exited in the study area.

Contents

1. Introduction

Geographic information system (GIS) is a tool for data input, storage, retrieval, manipulation, analyzing and output the spatial data (Marble et al., 1984). It can play a major role in spatial decision-making. Considerable effort is involved in information collection for the suitability analysis for crop production. The information should present both opportunities and constraints for the decision maker (Ghafari et al., 2000). GIS has the ability to perform numerous tasks utilizing both spatial and attribute data stored in it. It has the ability to integrate variety of geographic technologies like Global Positioning System (GPS) and Remote Sensing (RS). The ultimate aim of GIS is to provide support for spatial decisions making process (Foote and Lynch 1996). In multi-criteria evaluation many data layers are to be handled in order to arrive at the suitability, which can be conveniently achieved using GIS.

The process of land suitability classification is the evaluation and grouping of specific areas of land in terms of their suitability for a defined use. The suitability defines the level of the crop requirements with respect to the present soil/land characteristics. Matching the land characteristics with the factor ratings resulted in defining the suitability classes. Hence, suitability is a measure of how well the qualities of a land unit match with the requirements of a particular form of land use (FAO, 2003). Interpreting soil qualities and site information for the agriculture use and management practices is integrated using GIS (FAO, 1991; FAO, 2007). The land quality is a complex attribute of land which acts in a manner distinct from the actions of other land qualities in its influence on the land suitability for a specific kind of use (FAO, 1985); it is the ability of land to fulfill specific requirements for the land utilization type (LUT) (Van Diepen et al., 1991). Spatial analysis can be defined as the analytical techniques associated with the study of geographic phenomena locations together with their spatial dimensions and their associated attributes (ESRI, 2001).

The study area is considered one of the most important promising areas for horizontal expansion in land reclamation and utilization owing to its distinguishable location and the water abounding irrigation. The present study aims at GIS application for analyzing the spatial distributions of physical and chemical properties of the study soils to produce three land utilization types of irrigation (LUTs): surface irrigation (LUT1), drip-irrigated vegetables (LUT2) and drip-irrigated trees (LUT3).

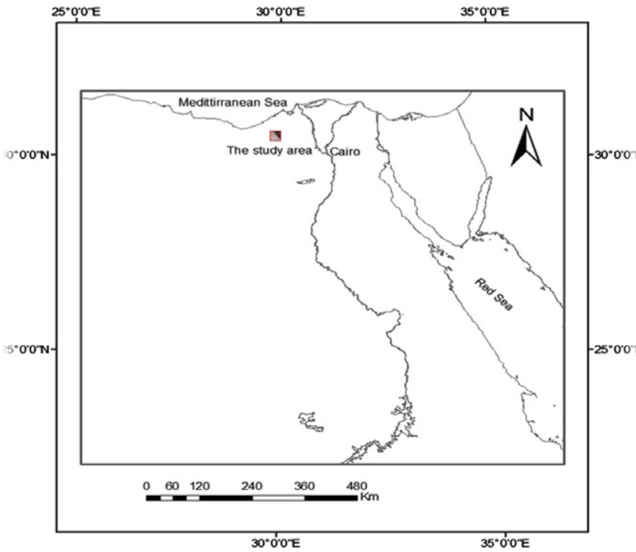

Figure 1 Location map of the study area.

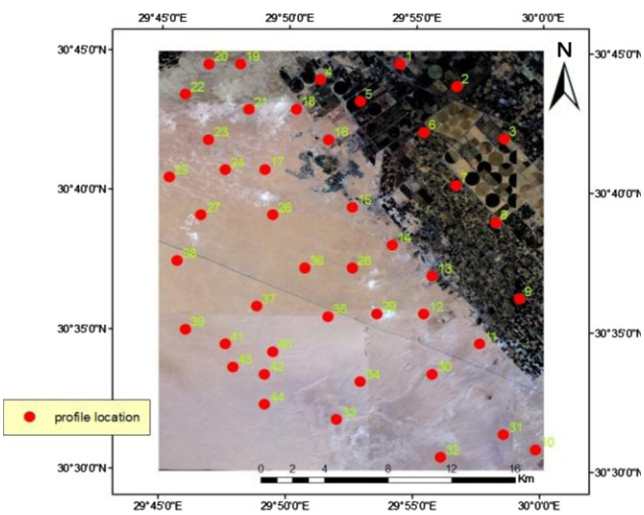

Figure 2 Soil profile locations on a rectified subset ETM$^+$ image (path 177- row 39).

2. Materials and methods

The study area is located in the northeast of the Western Desert between latitudes of 30°30′–30°45′N and longitudes of 29°45′–30°00′E (Fig. 1), covering about 670,881 km^2. The study area is considered as an extremely arid region where the maximum temperature (34.5 °C) was recorded in July and August, while the minimum one (7.5 °C) was recorded in January. The precipitation is rare and recorded only during November, December, January, February, March and April. The highest value 4.9 mm was recorded in January and the lowest one 0.8 mm was recorded in April. The lowest value of evaporation (1.8 mm/day) was recorded during January, while the highest value (7.9 mm /day) was recorded in June (Egyptian Metrological Authority, 2010). According to the American Soil Taxonomy (USDA, 2006), the soil temperature regime of the study area is thermic and the soil moisture regime is toric.

2.1. Source of data

- Topographic map with 1:50,000 scales produced by the Survey Authority of Egypt (1994).
- Satellite data (ETM$^+$ with path and row 177 and 39, respectively, acquired in 2006).

2.2. Field investigations

- Field profiles investigations were carried out in the study area and allocated using Global Positioning System (GPS) and Landsat ETM$^+$ image.
- Forty-four soil profiles representing the study area were allocated, exposed and morphologically described (FAO, 1990a; 1990b). One hundred and one soil samples were collected from the different profile horizons for laboratory analyses.
- Infiltration rate, Available water holding capacity (AWHC), drainage and erosion were determined according to Black (1982) and FAO (1976).

2.3. Laboratory analyses

- The soil samples were analyzed for particle size distribution, pH (in the soil paste), ECe (in the soil paste extract) and $CaCO_3$ according to USDA (2004) and exchangeable

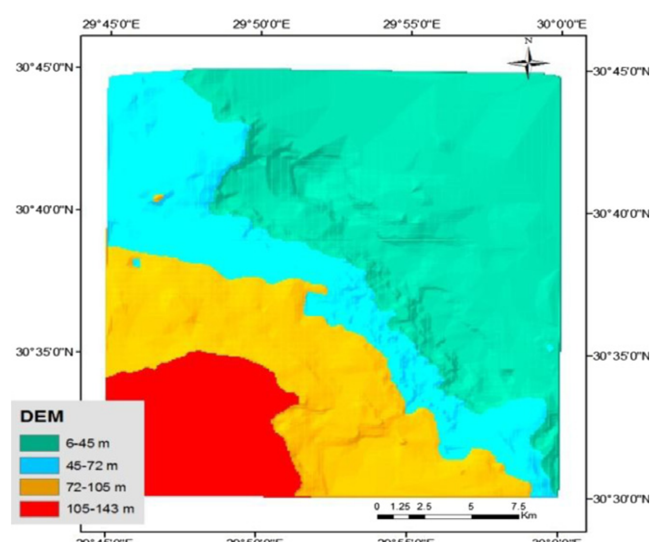

Figure 3 Digital elevation model (DEM) of study area.

Table 1 Average of some physical and chemical properties of the studied soil profiles.

Physiographic units	Profile No.	Slope (%)	Soil depth (cm)	Infil. rate* (mm/h)	AWHC (mm/100 cm)	Surface gravel (%)	Surface stone (%)	Surface boulder (%)	Surface horizon stones (%)	Rock outcrop (%)	$CaCO_3$ (%)	EC (ds/m)	ESP (%)	Texture	Erosion	Drainage
Plain	1	1	155	12	80	3	3	2	0	0	18	1.8	10	LS	Slight	Well
	2	1	155	13	80	0	0	0	0	0	25	1.6	11	LS	Slight	Well
	3	2	160	15	75	0	0	0	0	0	13	1.5	9	S	Slight	Well
	4	1	155	14	90	2	1	0	4	0	11	1.6	12	SL	Slight	Well
	5	1	155	10	95	0	0	0	3	0	4	6.4	13	SL	Slight	Well
	6	1	155	11	90	0	0	0	1	0	14	3.1	14	SL	Slight	Well
	7	2	150	16	75	0	0	0	0	0	11	1.5	8	S	Slight	Well
	8	1	165	18	75	11	2	1	3	0	9	2.5	7	S	Slight	Well
	9	2	155	15	85	2	1	1	15	0	13	2.6	12	SL	Slight	Well
Pediplain	10	8	160	16	75	2	2	1	1	20	7	1.1	6	S	Moderate	Well
	11	3	155	11	90	2	2	1	5	0	5	9.2	11	SL	Slight	Well
	12	2	155	10	175	25	10	10	15	0	16	22.5	14	SCL	Moderate	Well
	13	2	160	6	170	0	0	0	0	0	18	6.2	15	CL	Slight	Well
	14	3	120	15	70	5	5	3	20	0	4	7.9	10	LS	Moderate	Well
	15	3	160	7	175	25	5	4	4	0	4	1.6	14	SCL	Slight	Well
	16	8	160	7	180	10	2	1	2	0	13	8	14	SCL	Slight	Well
	17	2	10	16	75	13	11	12	10	0	9	2.2	7	S	Moderate	Poor
	18	2	155	8	170	3	2	1	14	0	17	7.5	13	SCL	Moderate	Well
	19	2	10	9	100	18	9	5	12	1	22	10	12	SL	Moderate	Poor
Terraces	20	2	40	10	110	14	12	13	0	0	36	1.2	12	SL	Moderate	Poor
	21	2	30	9	95	15	11	10	14	0	17	1.2	11	SL	Moderate	Poor
	22	2	20	9	100	4	12	14	0	0	13	2.5	12	SL	Moderate	Poor
Terraces	23	2	20	10	105	13	13	12	0	0	27	0.7	12	SL	Moderate	Poor
	24	2	20	11	95	14	11	13	20	0	7	3.5	10	SL	Moderate	Poor
	25	2	155	15	75	0	0	0	0	0	12	0.4	7	S	Moderate	Well
	26	3	10	12	80	13	10	15	50	0	44	1.4	11	SL	Moderate	Poor
	27	2	155	16	70	2	2	1	3	0	30	0.9	6	S	Moderate	Well
	28	3	160	16	70	20	15	5	0	0	18	1.3	7	S	Moderate	Well
	29	3	155	12	85	15	12	9	35	0	25	3.5	11	SL	Moderate	Well
	30	7	60	7	170	20	10	5	0	0	13	5	14	SCL	Moderate	Imperfect
	31	3	65	15	80	18	17	9	50	0	25	5.7	9	LS	Moderate	Imperfect
Foot slope	32	2	155	11	90	15	12	9	20	0	12	28.5	1	SL	Moderate	Well
	33	3	40	13	75	8	7	2	15	0	13	2.7	10	LS	Moderate	Imperfect
	34	2	55	11	95	13	11	10	15	0	17	9.1	12	SL	Moderate	Imperfect
	35	2	50	17	70	15	25	25	40	25	20	8.5	5	S	Moderate	Imperfect
	36	2	155	14	80	0	0	0	0	0	13	3.5	8	LS	Moderate	Well
	37	2	130	17	70	0	0	0	0	0	13	2.5	7	S	Moderate	Well
	38	3	50	17	70	0	0	0	0	0	17	1.2	7	S	Moderate	Imperfect
	39	2	125	10	85	0	0	0	0	0	19	1.3	11	SL	Moderate	Well
Table land	40	8	120	17	70	0	0	0	0	0	12	0.9	6	S	Moderate	Well
	41	3	90	18	70	0	0	0	0	0	16	4	5	S	Moderate	Moderate
	42	2	60	18	70	0	0	0	0	0	10	1.7	5	S	Moderate	Moderate
	43	2	80	15	75	0	0	0	0	0	15	3.5	7	LS	Moderate	Moderate
	44	2	40	14	75	0	0	0	2	0	17	2.6	8	LS	Moderate	Imperfect

S, sand; LS, loamy sand; SL, sandy loam; SCL, sandy clay loam; CL, clay loam; EC, electrical conductivity.
Infil. rate = infiltration rate; AWHC = available water holding capacity; ESP, exchangeable sodium content.

Table 2 Land suitability criteria for the different LUTs.

Criteria	LUTs			Suitability class
	LUT1	LUT2	LUT3	
Slope (%)	< 2	< 4	< 4	S1
	2–4	4–8	8-Apr	S2
	4–6	8–16	8–16	S3
	> 6	> 16	> 16	NS
Soil depth (cm)	> 150	> 100	> 150	S1
	100–150	50–100	100–150	S2
	50–100	25–50	50–100	S3
	< 50	< 25	< 50	NS
Erosion	–	Slight	Slight	S1
	–	Moderate	Moderate	S2
	–	Severe	Severe	S3
Soil drainage	Well	–	–	S1
	Moderate	–	–	S2
	Imperfect	–	–	S3
	Poor/very poor	–	–	NS
Infiltration rate (mm/h)	Aug-35	> 16	> 16	S1
	35–70	8–16	8–16	S2
	71–110	4–8	4–8	S3
	> 110	< 4	< 4	NS
Available water holding capacity (AWHC) (mm/100 cm)	> 160	> 110	> 110	S1
	90–160	75–110	75–110	S2
	50–90	50–75	50–75	S3
	< 50	< 50	< 50	NS
Surface gravel (%)	< 15	–	–	S1
	15–40	–	–	S2
	40–75	–	–	S3
	> 75	–	–	NS
Surface stones (%)	< 15	–	–	S1
	15–40	–	–	S2
	40–75	–	–	S3
	> 75	–	–	NS
Surface boulders (%)	< 3	–	–	S1
	15-Mar	–	–	S2
	15–40	–	–	S3
	> 40	–	–	NS
Total surface stoniness (%)	–	< 5	< 5	S1
	–	5–10	5–10	S2
	–	10–20	10-20	S3
	–	> 20	> 20	NS
Stone content of surface horizon (%)	–	< 5	< 5	S1
	–	5–10	5–10	S2
	–	10–20	10–20	S3
	–	> 20	> 20	NS
Rock outcrop (%)	< 5	< 2	< 2	S1
	5–10	2–5	2–5	S2
	10–20	5–10	5–10	S3
	> 20	> 10	> 10	NS
Soil salinity EC (ds/cm)	0–4	< 1	< 4	S1
	4–8	1–4	4–8	S2
	8–16	4–8	8–12	S3
	> 16	> 8	> 12	NS
Exchangeable sodium percent ESP (%)	0–8	0–15	0–15	S1
	15-Aug	15–25	15–25	S2
	15–30	25–35	25–35	S3
	> 30	> 35	> 35	NS
$CaCO_3$ (%)	–	< 30	< 30	S1
	–	30–40	30–40	S2
	–	40–60	40–60	S3
	–	> 60	> 60	NS

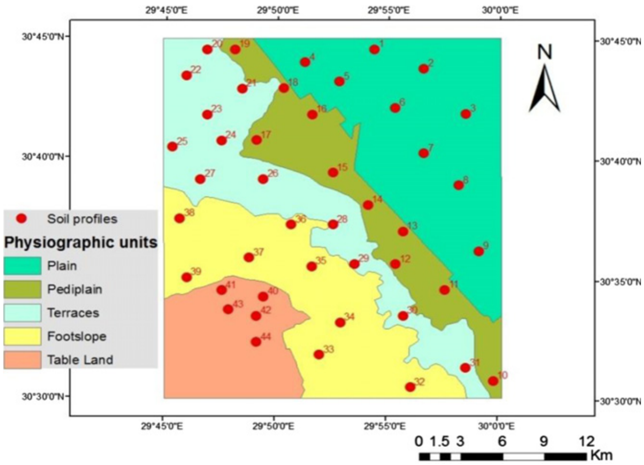

Figure 4 Physiographic units and soil profiles locations map of the study area.

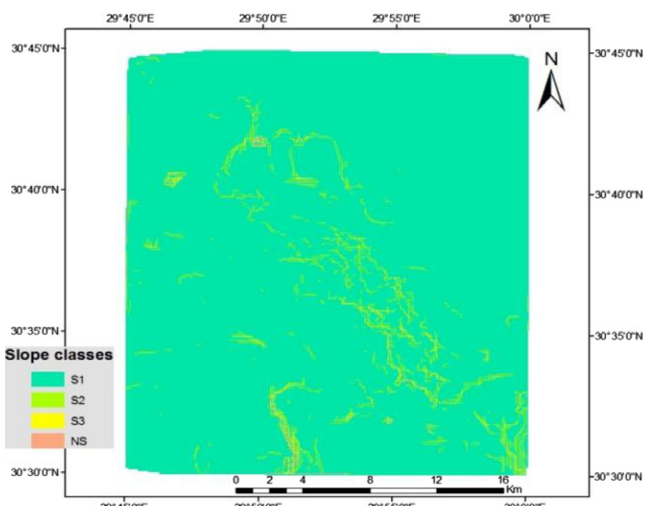

Figure 5 Slope suitability classes for LUT1.

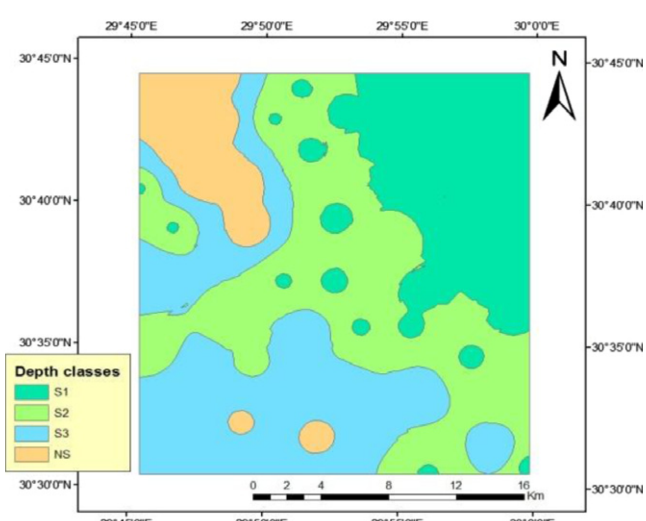

Figure 6A Soil depth suitability classes for LUT1 and 3.

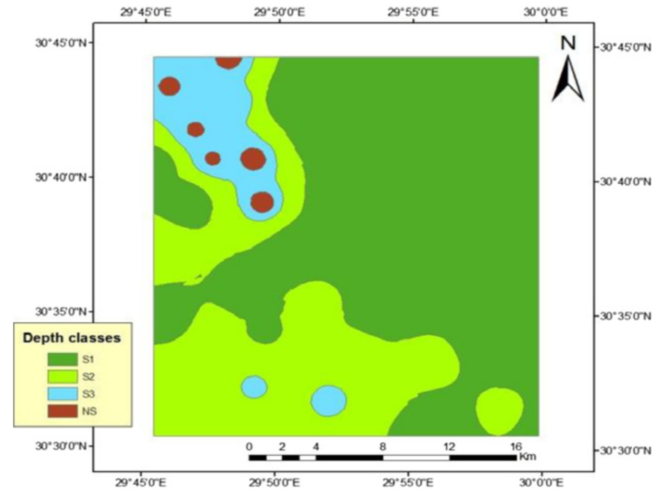

Figure 6B Soil depth suitability classes for LUT2.

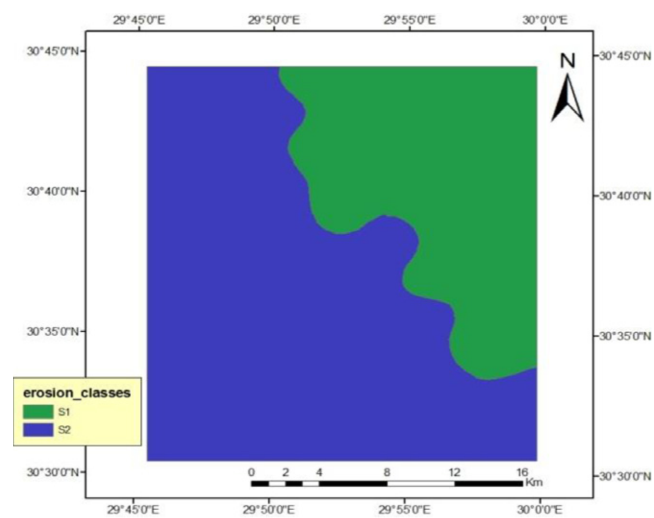

Figure 7 Soil erosion suitability classes for LUT2 and 3.

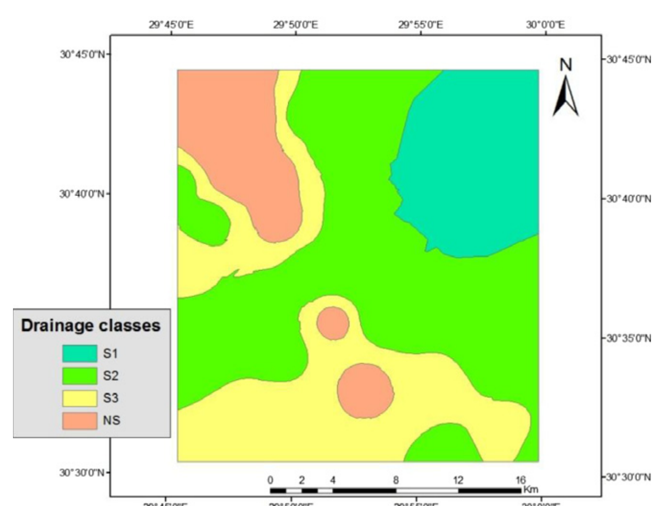

Figure 8 Soil drainage suitability classes for LUT1.

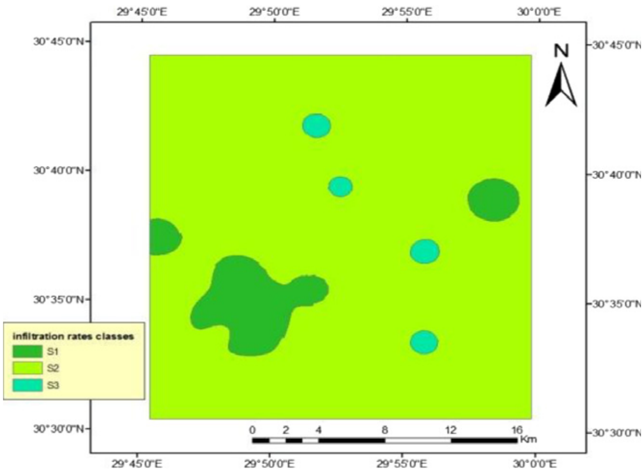

Figure 9 Soil infiltration rate suitability classes for LUT2 and 3.

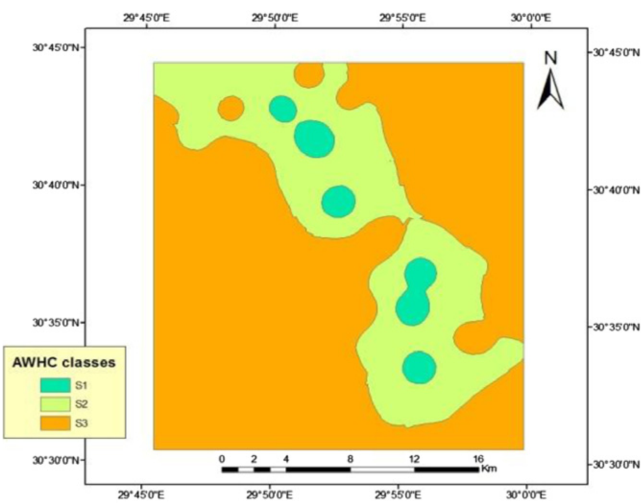

Figure 10A AWHC suitability classes for LUT1.

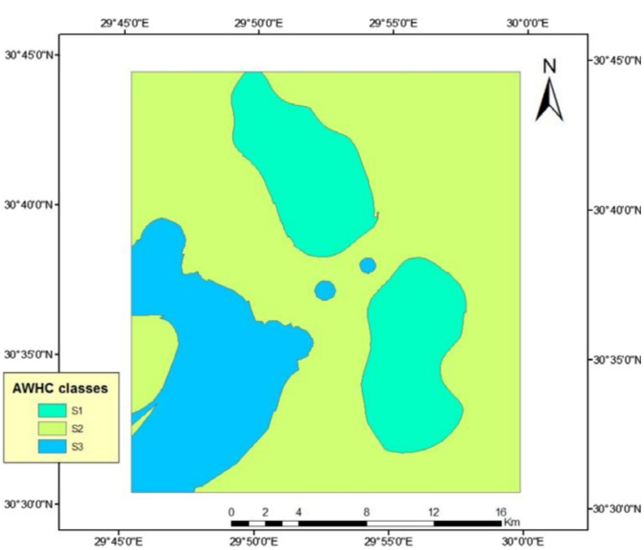

Figure 10B AWHC suitability classes for LUT2 and 3.

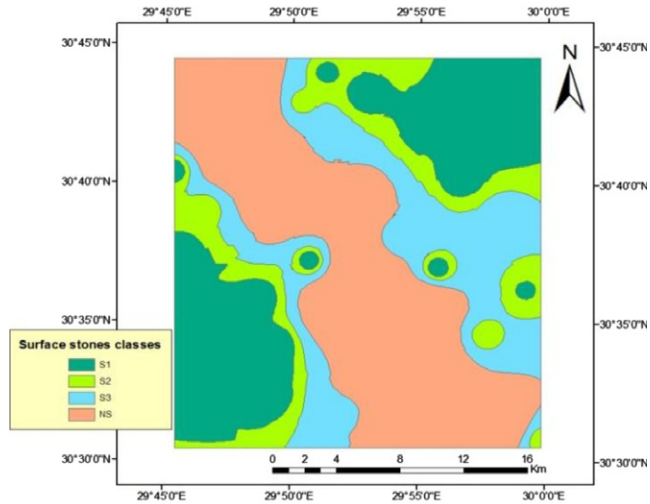

Figure 11 Surface stones suitability classes for LUT2 and 3.

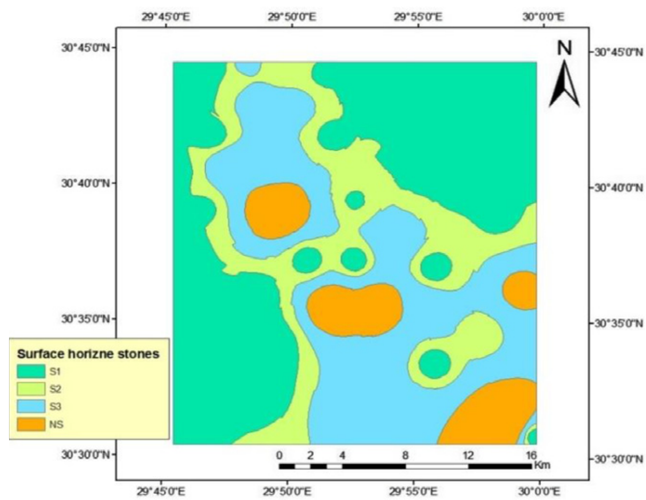

Figure 12 Surface horizon stones suitability classes for LUT2 and 3.

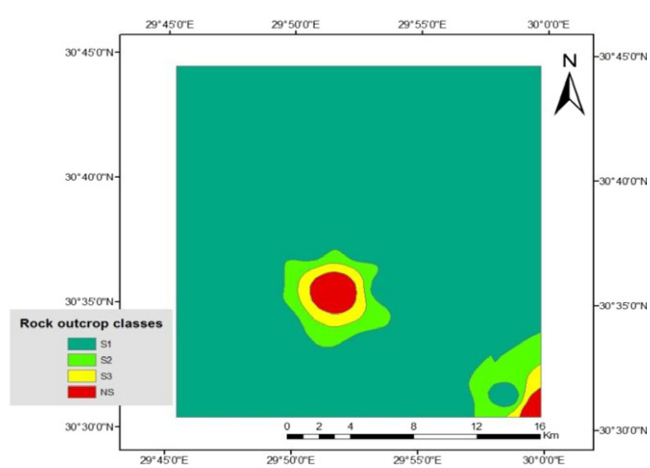

Figure 13 Rock outcrop suitability classes for LUT1.

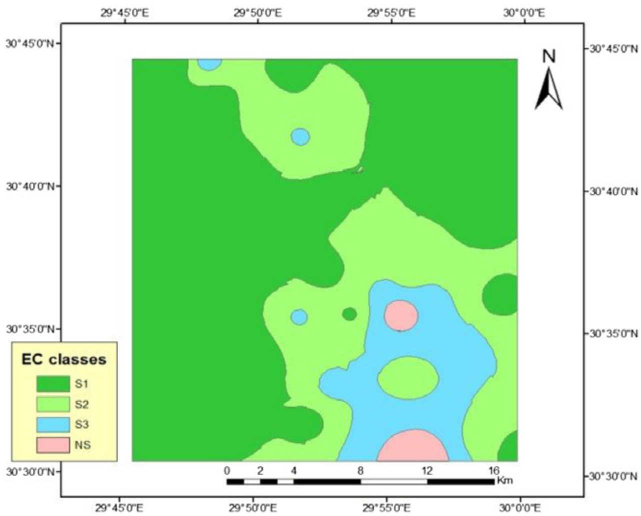

Figure 14A Soil salinity suitability classes for LUT .

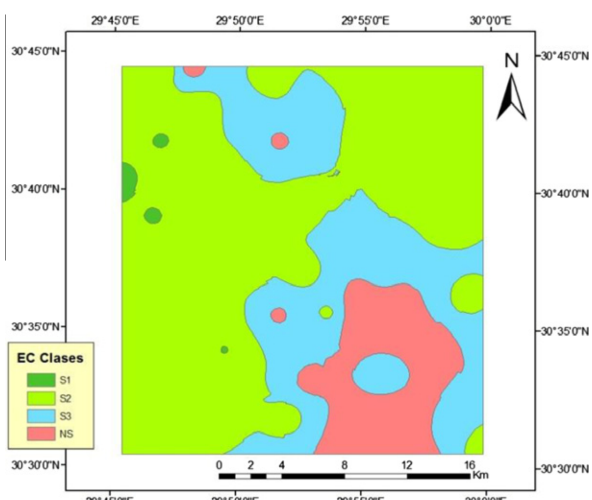

Figure 14B Soil salinity suitability classes for LUT2.

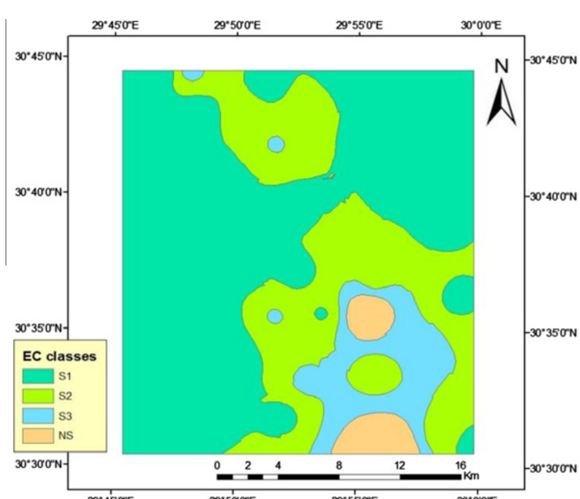

Figure 14C Soil salinity suitability classes for LUT3.

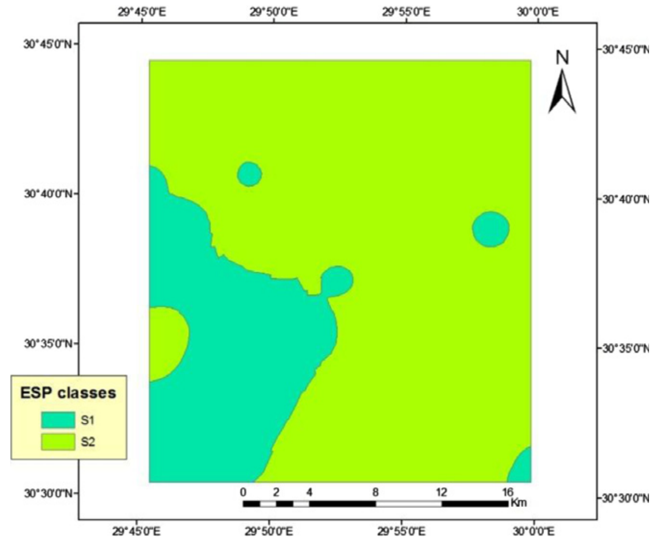

Figure 15 ESP suitability classes for LUT1.

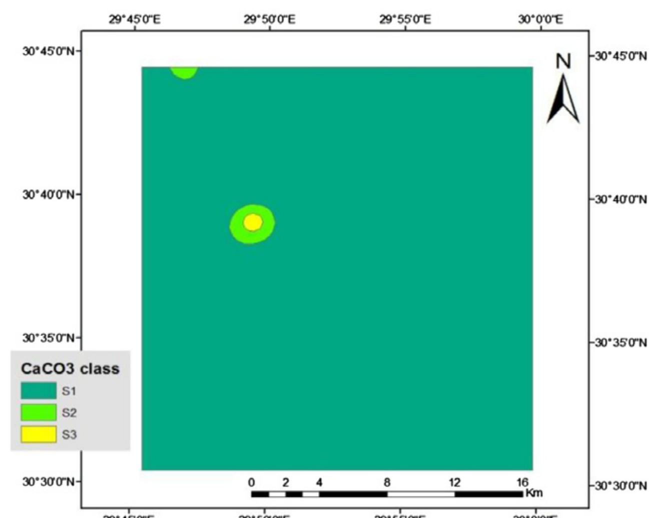

Figure 16 $CaCO_3$ suitability classes for LUT2 and 3.

sodium percent was determined according to Black (1982).

2.4. Geographic Information Systems (GIS) processes

- The topographic map was converted to digital form by scanning.
- The spatial data were geometrically corrected to world geographic coordinate system (WGS, 1984).
- On screen extraction and features analysis were achieved by the aid of Arc GIS 9.3 package.
- Triangulated Irregular Network (TIN) and digital elevation model (DEM) of the study area were built up by contour lines and spot heights extraction from the topographic map (1:50,000) and the analysis in Arc GIS 9.3 to produce slope map.

Table 3 Combined and final land suitability classes of the highlighted criteria for LUT1.

Profile no.	Slope	Depth	Infiltration rate	AWHC	Drainage	Surface gravel	Surface stone	Surface boulders	Rock outcrop	EC	ESP	Final suitability class
1	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
2	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
3	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
4	S1	S1	S1	S2	S1	S1	S1	S1	S1	S1	S2	S2
5	S1	S1	S1	S2	S1	S1	S1	S1	S1	S2	S2	S2
6	S1	S1	S1	S2	S1	S1	S1	S1	S1	S1	S2	S2
7	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
8	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S1	S3
9	S1	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
10	NS	S1	S1	S3	S1	S1	S1	S1	S3	S1	S1	NS
11	S2	S1	S1	S2	S1	S1	S1	S1	S1	S3	S2	S3
12	S1	S1	S1	S1	S1	S2	S1	S2	S1	NS	S2	NS
13	S1	S1	S1	S1	S1	S1	S1	S1	S1	S2	S2	S2
14	S2	S2	S1	S3	S1	S1	S1	S1	S1	S2	S2	S3
15	S2	S1	S1	S1	S1	S2	S1	S2	S1	S1	S2	S2
16	NS	S1	S1	S1	S1	S1	S1	S1	S1	S2	S2	NS
17	S1	NS	S1	S3	NS	S1	S1	S2	S1	S1	S1	NS
18	S1	S1	S1	S1	S1	S1	S1	S2	S1	S2	S2	S2
19	S1	NS	S1	S2	NS	S2	S1	S2	S1	S3	S2	NS
20	S1	NS	S1	S2	NS	S1	S1	S2	S1	S1	S2	NS
21	S1	NS	S1	S2	NS	S2	S1	S2	S1	S1	S2	NS
22	S1	NS	S1	S2	NS	S1	S1	S2	S1	S1	S2	NS
23	S1	NS	S1	S2	NS	S1	S1	S2	S1	S1	S2	NS
24	S1	NS	S1	S2	NS	S1	S1	S1	S1	S1	S2	NS
25	S1	S1	S1	S3	S1	S1	S1	S2	S1	S1	S1	S3
26	S2	NS	S1	S3	NS	S1	S1	S1	S1	S1	S2	NS
27	S1	S1	S1	S3	S1	S1	S1	S2	S1	S1	S1	S3
28	S2	S1	S1	S3	S1	S2	S2	S1	S1	S1	S1	S3
29	S2	S1	S1	S3	S1	S2	S1	S2	S1	S2	S2	S3
30	NS	S3	S1	S1	S3	S2	S1	S2	S1	S2	S2	NS
31	S2	S3	S1	S3	S3	S2	S2	S2	S1	S2	S2	S3
32	S1	S1	S1	S2	S1	S2	S1	S2	S1	NS	S2	NS
33	S2	NS	S1	S3	S3	S1	S1	S1	S1	S1	S2	NS
34	S1	S3	S1	S2	S3	S1	S1	S2	S1	S3	S2	S3
35	S1	S3	S1	S3	S1	S2	S2	S3	NS	S3	S1	NS
36	S2	S1	S1	S3	S1	S1	S1	S1	S1	S2	S2	S3
37	S1	S2	S1	S3	S1	S1	S1	S1	S1	S1	S1	S3
38	S2	S3	S1	S3	S3	S1	S1	S1	S1	S1	S1	S3
39	S1	S2	S1	S3	S1	S1	S1	S1	S1	S1	S2	S3
40	NS	S2	S1	S3	S1	S1	S1	S1	S1	S1	S1	NS
41	S2	S3	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
42	S1	S3	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
43	S1	S3	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
44	S1	NS	S1	S3	S3	S1	S1	S1	S1	S1	S2	NS

AWHC, available water holding capacity; EC, electrical conductivity; ESP, exchangeable sodium content.
S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; NS = non suitable.

- The main physiographic units of the region were identified by visual interpretation of Digital Elevation Model (DEM) and guided by both of GPS and Landsat ETM$^+$ image. The enhanced Landsat ETM$^+$ image is draped over the DEM and processed in ERDAS Imagine 9.2 software to define the different physiographic units following the geomorphic approach of Dobos et al. (2002) and Zinc and Valenzuela (1990).
- The suitability map of the land must be classified based on their land use quality priority for specified land use requirements. According to FAO (1976), generally land suitability map is classified into two classes i.e. Suitable and not suitable. These classes are further classified based on their benefits and limitations as in the following Table:

Suitability class	Description
S1	Highly suitable land without significant limitations
S2	Moderately suitable land that is clearly suitable but which has limitations that either reduce productivity or increase the inputs needed to sustain productivity compared with those needed on S1 land
S3	Marginally suitable land with limitations so severe that benefits are reduced and/or the inputs needed to sustain production are increased so that this cost is only marginally justified
NS	Not suitable land that cannot support the land use on a sustained basis, or land on which benefits do not justify necessary inputs

- Land suitability for three types of irrigated agricultural (LUTs) was based on the method of JAZPP (1997) that applied by The International Center for Agricultural Research in the Dry Areas (ICARDA) within the project named; Middle East water and livelihoods initiative (WLI, 2009). The suitability map was developed based on the requirements of the specified land use using 3D analysis and spatial analyst in Arc GIS 9.3.

3. Results and discussions

3.1. Physiographic units and their soil properties

Landsat ETM^+ image (Fig. 2), DEM map (Fig. 3) and data verification by in situ observation aided by GPS were used for delineating the main physiographic units (Fig. 4). Certain physical and chemical properties that are used to pursue LUTs are present in (Table 1). Brief descriptions of the soils of the different physiographic units are discussed hereafter:

3.1.1. Plain (200,538 km^2)

This unit is flat and the sloping is level. The most part of this unit is covered by plants that irrigated from El Naser Canal. This unit is characterized by deep effective soil depth (> 150 cm), sand to sandy loam texture, low content of surface stoniness, low content of surface horizon stones, mostly non saline soils(< 4 ds/m), and low ESP (< 15%). This unit is represented by profiles Nos. 1, 2, 3, 4, 5, 6, 7, 8 and 9 (Table 1).

3.1.2. Pediplain (97,965 km^2)

This unit is almost flat and nearly level and represented by profiles Nos.10, 11, 12, 13, 14, 15, 16, 17, 18 and 19. It is characterized by deep effective soil depth except profiles Nos. 17 and 19, varies in texture from sand to clay loam, presence of surface stoniness and surface horizon stones, mostly medium and high saline soils and low ESP (Table 1).

3.1.3. Terraces (141,792 km^2)

This unit is undulating and gently sloping and represented by profiles Nos. 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30

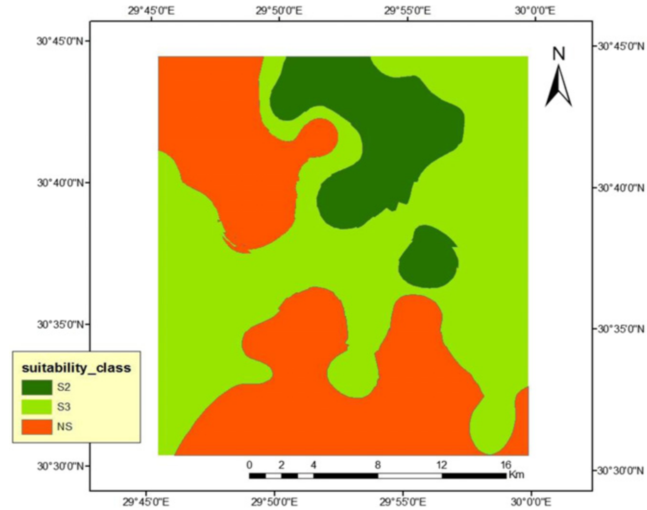

Figure 17 Final suitability classes for LUT1 of the study area.

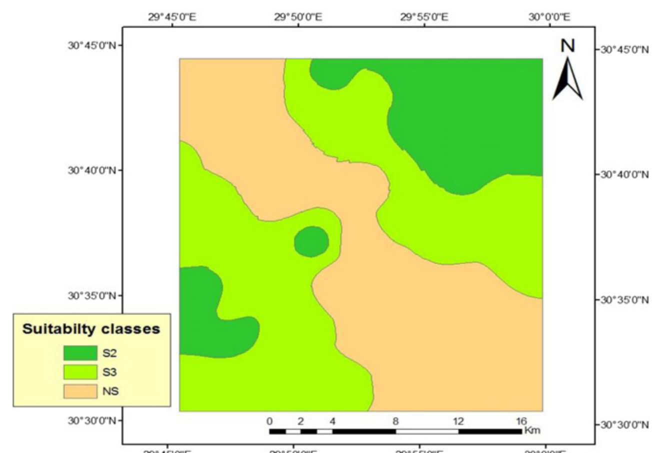

Figure 18 Final suitability classes for LUT2 of the study area.

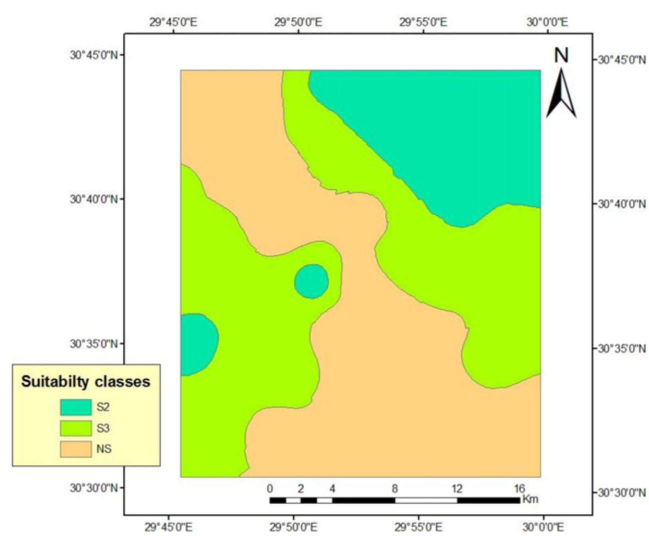

Figure 19 Final suitability classes for LUT3 of the study area.

Table 4 Combined and final land suitability classes the highlighted criteria for LUT2.

Profile no.	Slope	Depth	Infiltration rate	AWHC	Erosion	Surface stone	Surface horizon stone	Rock outcrop	$CaCO_3$	EC	ESP	Final suitability class
1	S1	S1	S2	S2	S1	S2	S1	S1	S1	S2	S1	S2
2	S1	S1	S2	S2	S1	S1	S1	S1	S1	S2	S1	S2
3	S1	S1	S2	S2	S1	S1	S1	S1	S1	S2	S1	S2
4	S1	S1	S2	S2	S1	S1	S1	S1	S1	S2	S1	S2
5	S1	S1	S2	S2	S1	S1	S1	S1	S1	S3	S1	S3
6	S1	S1	S2	S2	S1	S1	S1	S1	S1	S2	S1	S2
7	S1	S1	S2	S2	S1	S1	S1	S1	S1	S2	S1	S2
8	S1	S1	S1	S2	S1	S3	S1	S1	S1	S2	S1	S3
9	S1	S1	S2	S2	S1	S1	S3	S1	S1	S2	S1	S3
10	S2	S1	S2	S2	S2	S2	S1	NS	S1	S2	S1	NS
11	S1	S1	S2	S2	S1	S2	S2	S1	S1	NS	S1	NS
12	S1	S1	S2	S1	S2	NS	S3	S1	S1	NS	S1	NS
13	S1	S1	S3	S1	S1	S1	S1	S1	S1	S3	S1	S3
14	S1	S1	S2	S3	S2	S3	S3	S1	S1	S3	S1	S3
15	S1	S1	S3	S1	S1	NS	S1	S1	S1	S2	S1	NS
16	S2	S1	S3	S1	S1	S3	S1	S1	S1	S3	S1	S3
17	S1	NS	S2	S2	S2	NS	S2	S1	S1	S2	S1	NS
18	S1	S1	S3	S1	S2	S2	S3	S1	S1	S3	S1	S3
19	S1	NS	S2	S2	S2	NS	S3	S1	S1	NS	S1	NS
20	S1	S3	S2	S2	S2	NS	S1	S1	S2	S2	S1	NS
21	S1	S3	S2	S2	S2	NS	S3	S1	S1	S2	S1	NS
22	S1	NS	S2	S2	S2	NS	S1	S1	S1	S2	S1	NS
23	S1	NS	S2	S2	S2	NS	S1	S1	S1	S1	S1	NS
24	S1	NS	S2	S2	S2	NS	S3	S1	S1	S2	S1	NS
25	S1	S1	S2	S2	S2	S1	S1	S1	S3	S1	S1	S3
26	S1	NS	S2	S2	S2	NS	NS	S1	S2	S2	S1	NS
27	S1	S1	S2	S3	S2	S2	S1	S1	S1	S1	S1	S3
28	S1	S1	S2	S3	S2	NS	S1	S1	S1	S2	S1	NS
29	S1	S1	S2	S2	S2	NS	NS	S1	S1	S2	S1	NS
30	S2	S2	S3	S1	S2	NS	S1	S1	S1	S3	S1	NS
31	S1	S2	S2	S2	S2	NS	NS	S1	S1	S3	S1	NS
32	S1	S1	S2	S2	S2	NS	S3	S1	S1	NS	S1	NS
33	S1	S3	S2	S2	S2	S3	S3	S1	S1	S2	S1	S3
34	S1	S2	S2	S2	S2	NS	S3	S1	S1	NS	S1	NS
35	S1	S2	S1	S2	S2	NS	NS	NS	S1	NS	S1	NS
36	S1	S1	S2	S2	S2	S1	S1	S1	S1	S2	S1	S2
37	S1	S1	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
38	S1	S2	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
39	S1	S1	S2	S2	S2	S1	S1	S1	S1	S2	S1	S2
40	S2	S1	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
41	S1	S2	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
42	S1	S2	S1	S3	S2	S1	S1	S1	S1	S2	S1	S3
43	S1	S2	S2	S2	S2	S1	S1	S1	S1	S2	S1	S2
44	S1	S3	S2	S2	S2	S1	S1	S1	S1	S2	S1	S3

AWHC, available water holding capacity; EC, electrical conductivity; ESP, exchangeable sodium content.
S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; NS = non suitable.

and 31. It is characterized mostly by shallow effective soil depth, sand to sandy clay loam texture, presence of surface stoniness and surface horizon stones, non saline soils and low ESP (Table 1).

3.1.4. Foot slope (148,936 km^2)

This unit is undulating and sloping and represented by profiles Nos.32, 33, 34, 35, 36, 37, 38 and 39. It is have deep and shallow effective soil depth, presence of surface stoniness and surface horizon stones in some profiles, variable soil salinity from non saline to strongly saline and low ESP (Table 1).

3.1.5. Table land (81,650 km^2)

This unit is characterized by high relief and represented by profiles Nos. 40, 41, 42, 43 and 44. It is mostly have shallow effective soil depth, low content of surface stoniness, low content of surface horizon stones, non saline soils and very low ESP (Table 1).

Table 5 Combined and final land suitability classes of the highlighted criteria for LUT3.

Profile no.	Slope	Depth	Infiltration rate	AWHC	Erosion	Surface stone	Surface horizon stone	Rock outcrop	$CaCO_3$	EC	ESP	Final suitability class
1	S1	S1	S2	S2	S1	S2	S1	S1	S1	S1	S1	S2
2	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
3	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
4	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
5	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
6	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
7	S1	S1	S2	S2	S1	S1	S1	S1	S1	S1	S1	S2
8	S1	S1	S1	S2	S1	S3	S1	S1	S1	S1	S1	S3
9	S1	S1	S2	S2	S1	S1	S3	S1	S1	S1	S1	S3
10	S2	S1	S2	S2	S2	S2	S1	NS	S1	S1	S1	NS
11	S1	S1	S2	S2	S1	S2	S2	S1	S1	S3	S1	S3
12	S1	S1	S2	S1	S2	NS	S3	S1	S1	NS	S1	NS
13	S1	S1	S3	S1	S1	S1	S1	S1	S1	S2	S1	S3
14	S1	S2	S2	S3	S2	S3	S3	S1	S1	S2	S1	S3
15	S1	S1	S3	S1	S1	NS	S1	S1	S1	S1	S1	NS
16	S2	S1	S3	S1	S1	S3	S1	S1	S1	S2	S1	S3
17	S1	NS	S2	S2	S2	NS	S2	S1	S1	S1	S1	NS
18	S1	S1	S3	S1	S2	S2	S3	S1	S1	S2	S1	S3
19	S1	NS	S2	S2	S2	NS	S3	S1	S1	S3	S1	NS
20	S1	NS	S2	S2	S2	NS	S1	S1	S2	S1	S1	NS
21	S1	NS	S2	S2	S2	NS	S3	S1	S1	S1	S1	NS
22	S1	NS	S2	S2	S2	NS	S1	S1	S1	S1	S1	NS
23	S1	NS	S2	S2	S2	NS	S1	S1	S1	S1	S1	NS
24	S1	NS	S2	S2	S2	NS	S3	S1	S1	S1	S1	NS
25	S1	S1	S2	S2	S2	S1	S1	S1	S3	S1	S1	S3
26	S1	NS	S2	S2	S2	NS	NS	S1	S2	S1	S1	NS
27	S1	S1	S2	S3	S2	S2	S1	S1	S1	S1	S1	S3
28	S1	S1	S2	S3	S2	NS	S1	S1	S1	S1	S1	NS
29	S1	S1	S2	S2	S2	NS	NS	S1	S1	S1	S1	NS
30	S2	S3	S3	S1	S2	NS	S1	S1	S1	S2	S1	NS
31	S1	S3	S2	S2	S2	NS	NS	S1	S1	S2	S1	NS
32	S1	S1	S2	S2	S2	NS	S3	S1	S1	NS	S1	NS
33	S1	NS	S2	S2	S2	S3	S3	S1	S1	S1	S1	NS
34	S1	S3	S2	S2	S2	NS	S3	S1	S1	S3	S1	NS
35	S1	S3	S1	S2	S2	NS	NS	NS	S1	S3	S1	NS
36	S1	S1	S2	S2	S2	S1	S1	S1	S1	S1	S1	S2
37	S1	S2	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
38	S1	S3	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
39	S1	S2	S2	S2	S2	S1	S1	S1	S1	S1	S1	S2
40	S2	S2	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
41	S1	S3	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
42	S1	S3	S1	S3	S2	S1	S1	S1	S1	S1	S1	S3
43	S1	S3	S2	S2	S2	S1	S1	S1	S1	S1	S1	S3
44	S1	NS	S2	S2	S2	S1	S1	S1	S1	S1	S1	NS

AWHC, available water holding capacity; EC, electrical conductivity; ESP, exchangeable sodium content.
S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; NS = non suitable.

3.2. Soil suitability criteria for LUTs

Selection of suitable method of irrigation for particular soil type and terrain features is a key prerequisite for sustainable irrigation system (Negash, 2004). Physical and chemical properties of the soil as well as climatic data are the major factors that determine the land suitability of a given land. However, in the current investigation, physical and chemical soil properties (soil suitability criteria) were further evaluated to define the land suitability for three types of irrigated agricultural (JAZPP, 1997): (a) surface irrigation (LUT1); (b) drip irrigated vegetables (LUT2) and (c) drip irrigated trees (LUT3).

The soil suitability criteria for different LUTs of the study area (Table 1) include: slope gradient, soil depth, soil erosion, soil drainage, soil infiltration rate, available water holding capacity (AWHC), surface stoniness (gravel, stones and boulders), stone content of surface horizon, rock outcrop, soil salinity (EC), exchangeable sodium percent (ESP), and calcium carbonate content.

The soil suitability criteria that used to define the suitability classes (S1, S2, S3 and NS) for the different LUTs are listed in (Table 2).

3.3. Land suitability classes for LUTs

The final land suitability maps of the study area for different LUTs was developed by multiplying the reclassified factors map and adding them by Raster calculator technique in spatial analyst module of Arc GIS 9.3 software. The values which are obtained from the result are classified into suitability classes based mainly on field observations.

3.3.1. Combined and final suitability for LUT1

According to JAZPP (1997), the suitability of soils for LUT1 is depending on the following land suitability criteria: slope gradient (Fig. 5), soil depth (Fig. 6A), soil drainage (Fig. 8), soil infiltration rate, available water holding capacity (AWHC; Fig. 10A), surface gravel, surface stones, surface boulders, rock outcrop (Fig. 13), salinity (EC; Fig. 14A) and exchangeable sodium percent (ESP; Fig. 15). The combined and final suitability classes of the highlighted variables for LUT1 are obtained in (Table 3) and Fig. 17. The marginally suitable (S3) class is dominating the study area followed by non suitable class (NS); however, the moderately class (S2) was the least abundant.

3.3.2. Combined and final suitability for LUT2 and LUT3

The soil suitability criteria for LUT2 and LUT3 are: slope gradient, soil depth (Figs. 6A and 6B), soil erosion (Fig. 7), soil infiltration rate (Fig. 9), available water holding capacity (AWHC; Fig. 10B), total surface stones (Fig. 11), stone content of surface horizon (Fig. 12), rock outcrop, salinity (EC; Figs. 14B and 14C), exchangeable sodium percent (ESP) and total calcium carbonate content (Fig. 16). The combined and final suitability classes of the former variables are listed in (Tables 4 and 5) and (Figs. 18 and 19). The suitability classes for LUT2 and LUT3 are more or less similar as shown in (Figs. 18 and 19).

The data indicate that S3 and N classes are dominating the study area as described for LUT1 with less abundant by S2, of course with differences in areas of the corresponding suitability classes.

In conclusion, the most soil limiting factors in the study area for surface irrigation (LUT1) are soil depth and soil drainage, followed by slope gradient, salinity and AWHC. However, the most limiting factors for drip irrigation (LUT2 & 3) are surface stones and soil depth followed by stone content of surface horizon and salinity. Land improvements are required to correct or reduce the severity of limitations exited in the study area as follows:

a- Application of fine fraction (e.g. shale) to the sandy soils improve the soil drainage and AVHC and consequently reduce the limiting factors for LUT1, 2 and 3.
b- Stone removal from the surface and surface horizons by modern techniques to improve the suitability class of LUT2 and 3.
c- Salinity removal by leaching with low saline water and consequently raised the rank of suitability class for LUT1, 2 and 3, and,
d- Chemical and organic fertilizers application in addition to soil conditioners to increase soil fertility and improve the physical and chemical properties of the soil.

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