



Modeling crop suitability under micro irrigation using a hybrid AHP-GIS approach

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Abstract

Crop suitability analysis using novel models is a pillar for sustainable land-use planning. In this work, the analytical hierarchy process (AHP) was integrated with GIS to produce suitability maps for wheat and maize under sprinkler irrigation and broad bean under drip irrigation. The study was conducted in an arid area, west Nile Delta of Egypt. The characteristics of local climate, landscape, and groundwater quality were matched with crop requirements and assigned scores. A GIS-based model was implemented to integrate scores and AHP weights and generate crop suitability maps. The climate conditions fitted optimum crop requirements; however, slight slope limitations affected wheat and maize. The electrical conductivity (EC), exchangeable sodium percentage, and CaCO₃ were the most important soil factors affecting broad bean, and these factors besides coarse fragments affected wheat and maize. The EC, Na⁺, and Cl⁻ were the most influential factors for wheat and maize irrigation, while EC and sodium adsorption ratio had the greatest priority for broad bean irrigation. Irrigation water quality had the highest specific weight (0.38) followed by soil (0.36), slope (0.15), and climate (0.10). The final suitability maps showed that 97 and 3% of the total area were suitable (S2) and moderately suitable (S3) for wheat, respectively. Moreover, 85 and 15% of the total area fitted the S2 and S3 classes for broad bean. For maize, 36 and 64% of the total area fitted the S2 and S3 classes. Integrating AHP and GIS would provide effective land-use planning and also suggest proper management practices in arid areas.

Keywords Food crops · AHP · GIS modeling · Sprinkler irrigation · Drip irrigation · Land-use planning

Introduction

With the burgeoning global population, expanding the irrigated agriculture is of great importance to achieve a sufficient food supply (Singh 2021). The agricultural reclamation through converting the desert ecosystems into croplands provides a great potential for utilizing arid lands, combating desertification (Hu et al. 2021), and mitigating climate change (Everest

and Gür 2022). However, land and water resources in many arid regions are affected by severe limitations that threaten sustainable irrigated agriculture (Abuzaid and Jahin 2021). Climate (high temperature and low rainfall) and soil limitations (salinity, sodicity, lime, and stoniness) are dominant in arid and desert ecosystems. Moreover, due to water shortage, groundwater with poor qualities is extensively used in irrigation (Jafari et al. 2018). These factors put abiotic stresses on the growing plants and finally lead to yield reduction based on the degree of crop tolerance (Wassif and Wassif 2021). The climate change is expected also to accelerate the depletion of natural resources, posing a heavy pressure on the arable lands (Everest et al. 2021a). Therefore, integrated management of land and water resources is essential for sustainable socio-economic development (Loiskandl and Nolz 2021).

The initial step for successful agricultural development in the newly-reclaimed desert areas is assessing the fitness of natural resources for crop production (Abdellatif and Abuzaid 2021). This can be done through matching characteristics of local climate and landscape (topography and soil)

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with crop requirements (Sys et al. 1993). This procedure is a multi-criteria decision analysis (MCDA) since a large number of spatial and non-spatial attributes are utilized in decision making (Kazemia et al. 2016). This renders a huge challenge on regional-scale planning, and thus integrating geographic information systems (GIS) and MCDA is a powerful tool for decision making (Mohamed et al. 2019). Abd El-Kawy et al. (2010) used GIS-MCDA to develop the Agricultural Land Evaluation System for arid and semi-arid regions (ALESarid-GIS) considering climate, soil, and irrigation water data. The ALESarid-GIS software can provide a reasonable accuracy, ease of application, and moderate data demand (Elnashar et al. 2021). Therefore, this system has been used as a decision support system for land-use planning in many areas in Egypt such as west Nile Delta, (Elsemary et al. 2013; Abd El-Kawy et al. 2019), El-Omayed area in the north-coastal of Egypt (Darwish et al. 2015), El-Fayoum depression (Shokr et al. 2021), and areas adjacent to Lake Nasser in Aswan Governorate (Elnashar et al. 2021). However, one of the main disadvantages of the ALESarid-GIS is the equal significance for all criteria used for land evaluation. This is because each criterion has a degree of importance that differs according to the prevailing ecological conditions and dominant limitations (Everest et al. 2021b; Everest and Gür, 2022).

A real estimation of site suitability for a specific crop requires quantifying the degree of influence of each criterion on crop performance (Pilevar et al. 2020). Such relative importance (weight) can be estimated using multiple-attribute decision-making methods like TOPSIS, ELECTRE, PROMETHEE, Gray relational model, and the analytical hierarchy process (AHP) (Tzeng and Huang 2011). The AHP prioritizes the criteria according to a score derived from the opinions of experts (Saaty 2008). This approach provides a dynamic and flexible weighting scheme as it allows modifying criteria and hierarchical structures (Kazemia et al. 2016). It is valuable when the specification of certain relationships among large numbers of criteria is too difficult (Everest et al. 2021b). Moreover, this approach enables identifying weights for both individual or grouped criteria, providing applicability in various aspects of land evaluation studies (Abuzaid et al. 2022). The hybrid GIS-AHP approach has been employed for mapping land suitability for wheat in a hyper-arid area in Egypt (Mohamed et al. 2019) and a semi-arid region of Turkey (Dedeoglu and Dengiz 2019). The crop classifications gave reliable results with highly significant correlations with actual yields. Kazemia et al. (2016) integrated GIS with AHP to assess land suitability for rain-fed broad bean cropping in a semi-arid area of Iran. They indicated that this combination could provide a practical and applicable method for land suitability. Further studies on irrigated lands used a GIS-AHP method for maize suitability (Tashayo et al. 2020a) and fuzzy AHP-GIS for wheat (Tashayo et al. 2020b). They highlighted the high potentiality of

these combinations for site-specific soil management and land-use planning.

The cereals and pulses are consumed as a staple food in both developing and developed countries around the world and serve as a source of nutrients as well as dietary energy (Shahzad et al. 2021). They are the dominant field crops in the drylands, providing the food supply for the most population, feed requirement for animals, and source for exports (Osman 2018a). Moreover, these crops provide high yields of residues that can be recycled for the production of organic fertilizers (compost), bioenergy, and biofuels (Frouz and Frouzová, 2022). This, in turn, can significantly contribute to sustainable agroecosystem services, environment protection, and mitigating climate change through reducing the emission of greenhouse gasses (Everest et al. 2021a; Kareem et al. 2022). In recent years, increasing the cultivated areas with cereals and pulses has gained attention in the dryland agroecosystems. Hence, crop suitability models have been developed for several crops such as wheat and maize (Pilevar et al. 2020), broad bean (Kazemia et al. 2016), and chickpea (Nabati et al. 2020). They focused on analyzing climate and land characteristics with little attention to irrigation water quality. Mohamed et al. (2019) used irrigation water salinity besides soil and slope factors as input parameters in modeling wheat suitability. However, irrigation water quality relies also on further aspects, i.e., infiltration, toxicity, and other problems. These problems are mostly relevant to plant species, soil type, and irrigation type (Ayers and Westcot 1994). Therefore, water quality should be assessed based on crop requirements under different soil conditions and irrigation systems.

In hot desert areas, water availability in terms of quantity and quality is one of the main constrain for agroecosystem balance (Bouallala et al. 2020). Therefore, available water resources should be used more efficiently sustainably to fulfill crop requirements (Sidhu et al. 2021). In this context, modern irrigation technology helps in integrated water management for sustainable irrigated agriculture (Abdellatif and Abuzaid 2021). The two systems of micro-irrigation, including drip irrigation and sprinkler irrigation, can maximize water productivity and at the same time stabilize crop yield (Loiskandl and Nolz 2021). Compared with surface methods, micro-irrigation provides uniform wetting and considerably reduce losses, and thus improving water use efficiency (Sidhu et al. 2021). Moreover, water-soluble nutrients and pesticides can be applied more efficiently and precisely along with irrigation, thereby saving fertilizers and increasing crop yield (Reddy 2016). Micro-irrigation also enhances the ability to adapt to limitations such as salinity, sodicity, coarse texture, lime, and sloping surfaces (Osman 2018b; Mihalikova and Dengiz 2019; Wassif and Wassif 2021). Micro-irrigation enables effective irrigation scheduling, which plays important role in reducing soil CO₂

emission and CH₄ uptake by the growing plants (Mehmood et al. 2021).

The major food crops in Egypt are wheat, maize, and broad bean and represent major contributions to human diets. Official statics (CAPMAS 2020) revealed current production-consuming gaps estimated by 65.3, 50.1, and 87.6% for these crops, respectively. Thus, increasing the cultivated areas in the newly-reclaimed desert lands adopting modern farming systems should take priority (Abdellatif and Abuzaid 2021). This, in turn, entails a precise matching of the locally-dominant conditions (climate, landscape, and water) with the crop requirements through spatial models (Mohamed et al. 2019). At regional scales, traditional crop suitability analyses have been increasingly conducted in many desert areas in Egypt (Abuzaid and Fadl 2016; Fadl and Abuzaid 2017; Abd El-Kawy et al. 2019; Elnashar et al. 2021). However, there is quite limited information about the specific effect of each criterion in crop-based land evaluation studies, especially under micro-irrigation. For this motivation, the current work was conducted to provide a novel

approach through integrating AHP as a MCDA technique with GIS tools for modeling site suitability for cultivating wheat, maize, and broad bean under modern irrigation techniques. The model was then applied in a newly developed desert area located in west Nile Delta, Egypt, to select the optimum crop and specify dominant limitations for achieving sustainable land-use planning.

Materials and methods

The study area

The study was conducted within 1256.60 km² (125,660 ha), west of the Nile Delta, Egypt. The geographic location is UTM zone 36 between 30° 14' 55.56" to 30° 35' 24.59" N and 30° 20' 8.04" to 30° 48' 13.45" E (Fig. 1). The climate data (Fig. 2) collected from Wadi Al-Natron station (latitude: 30° 24' 00" N, longitude 31° 01' 00" E, elevation: 17 m) indicate that the minimum temperature (8.2 °C)

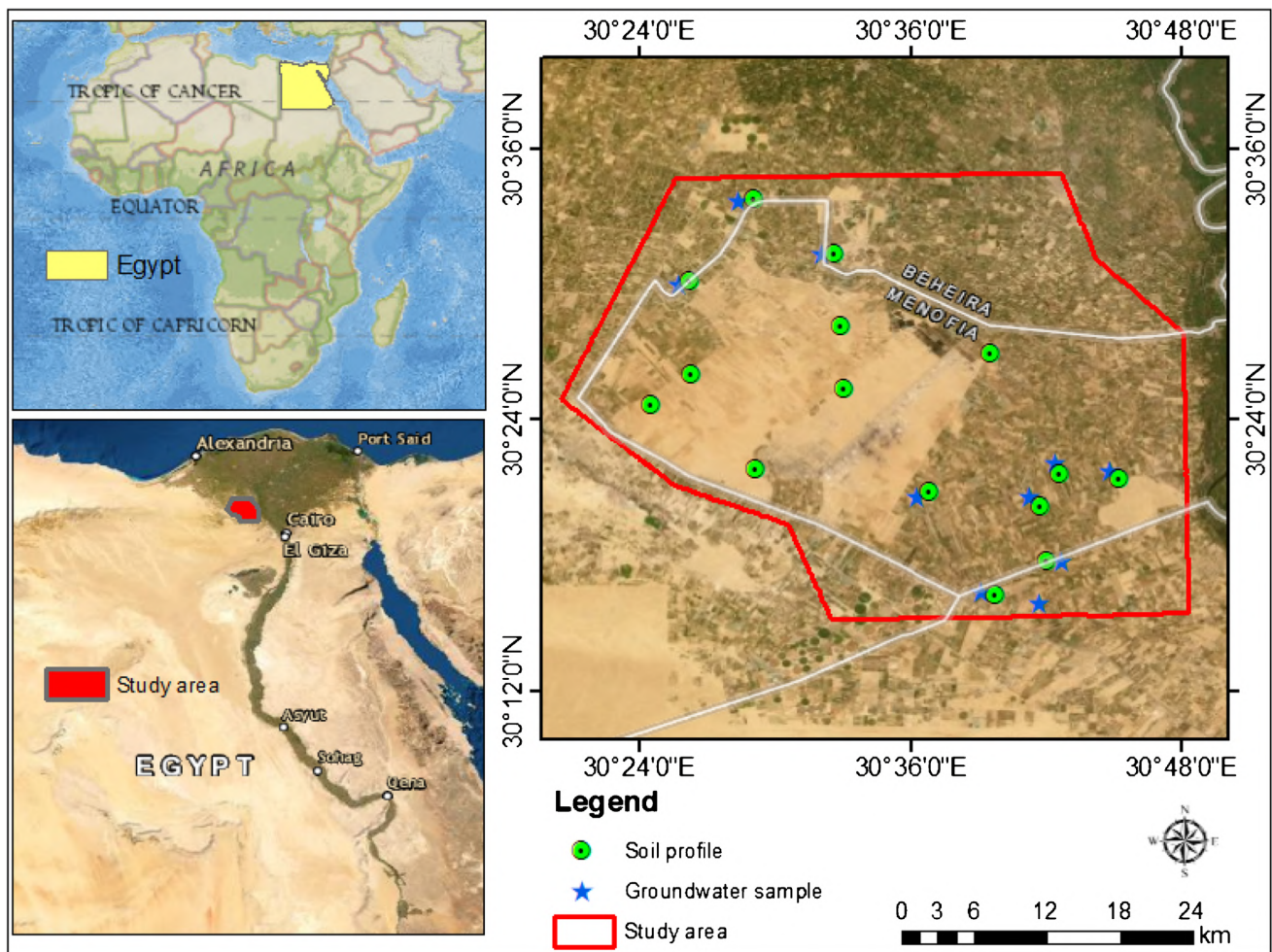
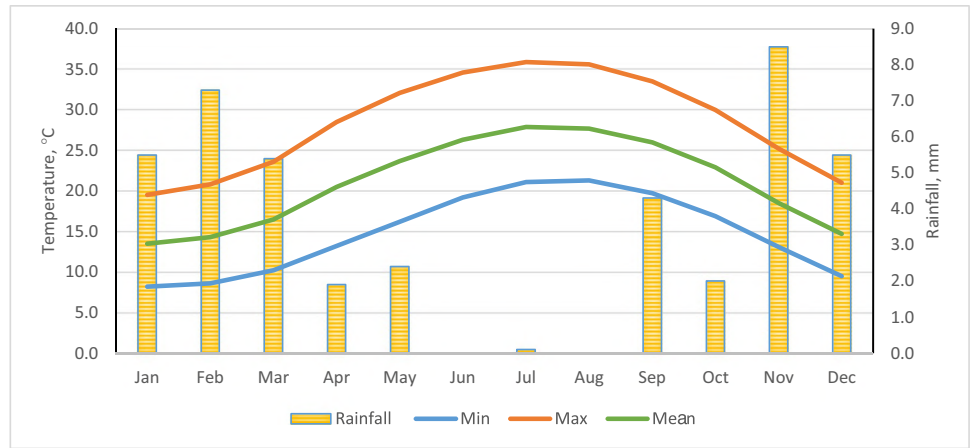


Fig. 1 Location maps of the studied area

Fig. 2 Mean monthly temperature and rainfall in the studied area (from 2005 to 2020)



occurs in January, while the highest one (35.9 °C) occurs in July. The mean annual temperature is 21.0 °C and the total annual rainfall is 43 mm. According to Soil Survey Staff (2014a), the soil temperature regime is “Thermic” and the soil moisture regime is “Torric.”

The digital elevation model (DEM of 30-m resolution) indicates that the elevation from the sea level ranges from 3 to 111 m and the slope varies from 0 to 59% (Fig. 3). According to CONCO-Coral/EGPC (1987), the area is underlain by Late Tertiary (Pliocene) and Quaternary sediments. The Pliocene sediments (El Hagif formation) are composed of limestone with marl inter-beds. The Quaternary sediments are composed of sand, silt, clay, and gravel.

The area is dominated by three land-use/land-cover patterns: barren lands (50.62%), cultivated lands (48.97%), and urban areas (0.41%). The area is mainly cultivated with fruit crops (citrus, peach, grape, and olive). Groundwater is the main source for irrigation and other activities.

Geomorphic map

One scene (path 177/row 39) of Landsat 8 operational land imager (OLI) dated to June 2021 was acquired (USGS Earth Explorer gateway). The ENVI 5.1 software was used for digital image processing. The atmospheric correction (FLASH module), stretching, band stacking, and spatial and

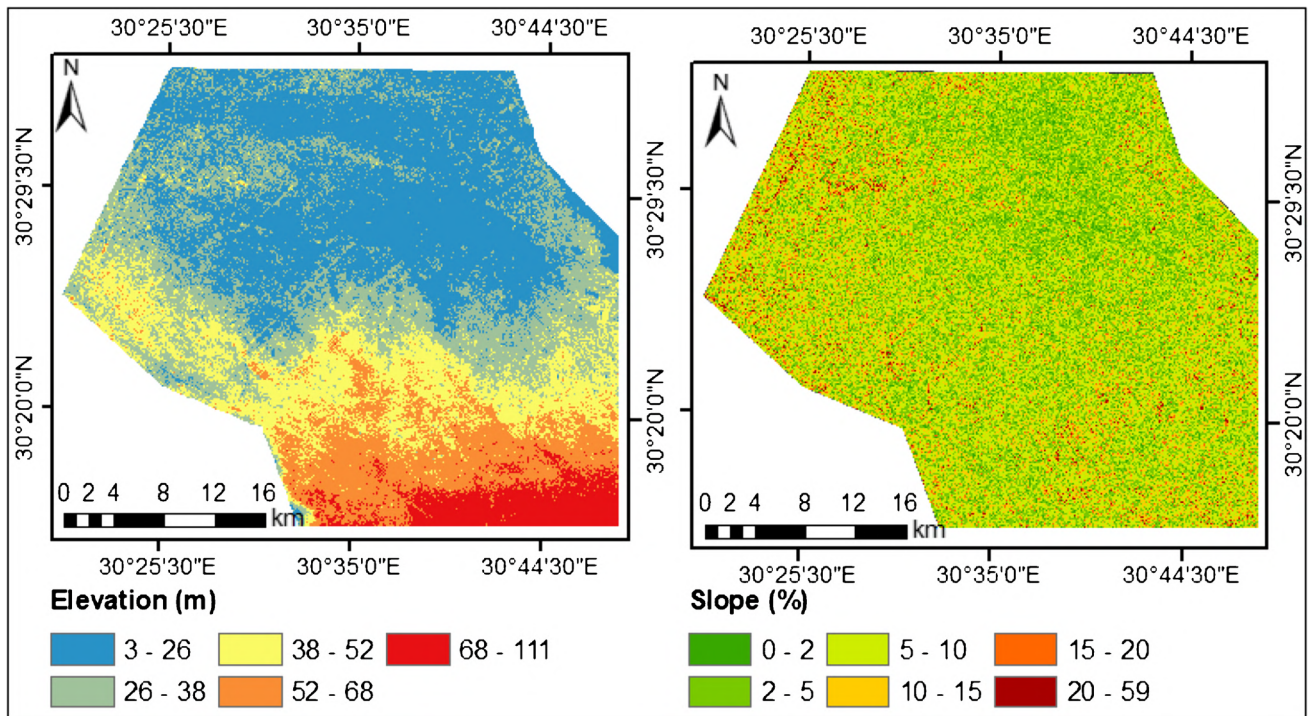


Fig. 3 Maps of elevation and slope in the studied area

spectral subsets were done. An unsupervised classification (ISO DATA classifier) followed by a supervised classification (maximum likelihood) was executed. Based on the processed OLI imagery, DEM, geological map (CONCO-Coral/EGPC 1987), and field surveys, mapping units were delineated (Zinck et al. 2016) within ArcGIS 10.8 software (ESRI Co, Redlands, USA).

Field work and laboratory analyses

Fifteen geo-referenced soil profiles (Fig. 1) were dug to a 150-cm depth or a lithic contact and their morphological features were observed according to FAO (2006). Soil samples were collected from the subsequence horizons and kept in polyethylene bags to be transported to the laboratory. Ten groundwater samples were collected from artesian wells. In situ measurements of water pH and electrical conductivity (EC) were done using a portable HACH instrument (HQ 40d, multi, USA). Thereafter, water samples were collected in high-density polypropylene bottles of 1 L and transported to the laboratory. Further water analyses were performed according to APHA (2017).

Soil analyses were performed according to Soil Survey Staff (2014b). The samples were air-dried, crushed, and passed through a 2-mm mesh and coarse fragment (> 2 mm) content by volume was recorded. The particle size distribution was done (standard international pipette method). The pH was measured in the 1:2.5 soil–water suspension,

while EC was measured in the soil paste extract. The organic carbon (OC) was determined using the Walkley–Black procedure. Cation exchange capacity (CEC) and exchangeable sodium parentage (ESP) were determined using ammonium acetate method. The total CaCO₃ content was determined using Collin’s calcimeter, while gypsum content was determined using the acetone precipitation method.

Modeling crop suitability

The diagram of crop suitability modeling is shown in Fig. 4. The crop requirements (Table 1) were combined through available scientific resources (Sys et al. 1993; Ayers and Westcot 1994; Kazemia et al. 2016; Mihalikova and Dengiz 2019; Pilevar et al. 2020; Tashayo et al. 2020a, b). This is in addition to national standards set by the Ministry of Agriculture and Land Reclamation for cultivating wheat (ARC 2000), maize (ARC 2008), and broad bean (ARC 2005). The major groups of criteria (climate, topography, soil, and irrigation water) include sub-criteria, except topography that was expressed by slope only (Table 1). According to crop requirements, sub-criteria were classified into five suitability classes (FAO 1976), i.e., highly suitable (S1), moderately suitable (S2), marginally suitable (S3), currently not suitable (N1), and permanently not suitable (N2).

The procedure suggested by Saaty (2008) was adopted to prioritize the major criteria and their sub-criteria. Firstly, a pairwise comparison matrix (PCM) ($n = 4$) was established

Fig. 4 Schematic outline of the methodology applied for modeling crop suitability

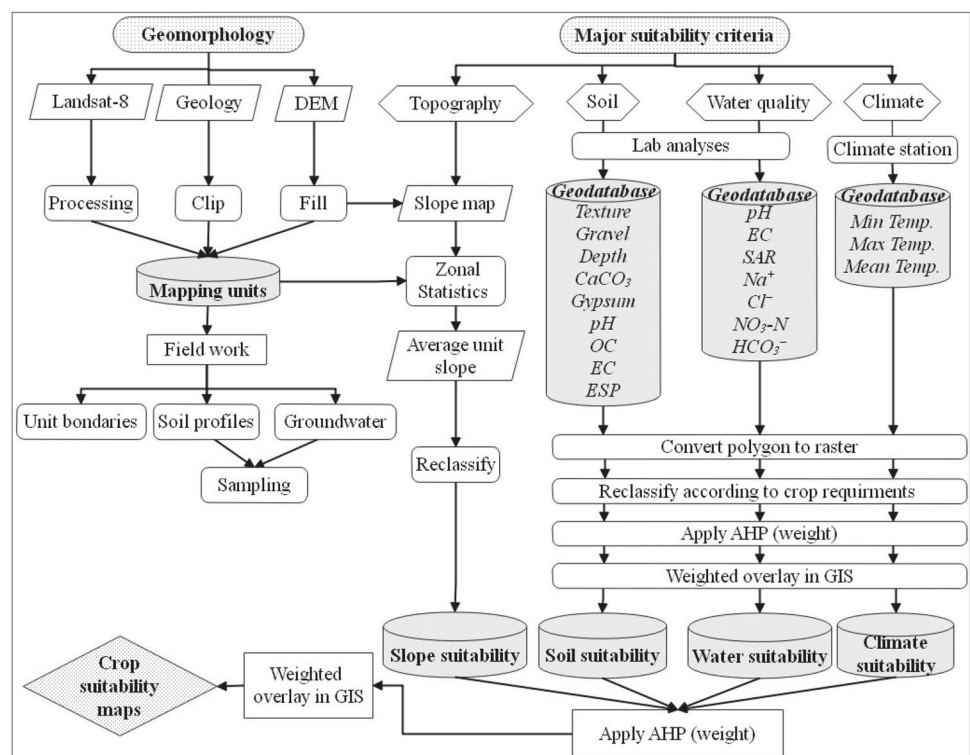


Table 1 Criteria and sub-criteria used for delineating crop suitability in the studied area

Criteria	Sub-criteria	Crop	Class, rating scale and limitation degree					
			S1	S2	S3	N1	N2	
Climate	Mean temperature at growth period, °C	Wheat	18–20	23–23	23–25	25–30	>30	
		Maize	18–15	15–12	12–10	10–8	<8	
	Broad bean	18–25	22–18	18–16	16–14	<14		
		18–25	26–32	32–35	35–40	>40		
	Minimum temperature at growth period, °C	Wheat	10–15	15–18	12–15	10–12	<10	
		Maize	17–16	25–28	28–30	30–32	>32	
	Maximum temperature at growth period, °C	Wheat	20–25	8–10	6–8	--	<6	
		Maize	17–18	16–12	12–9	9–7	<7	
	Topography	Slope, %	Broad bean	10–15	18–24	24–28	28–30	>30
			Wheat	20–25	8–10	6–8	6–4	<4
Maize		24–28	25–27	27–32	--	>32		
		Broad bean	20–25	28–32	32–36	--	>36	
Gravel, %		Wheat	0–2	2–4	4–8	8–16	>16	
		Maize	0–2	2–4	4–8	8–16	>16	
Texture		Broad bean	0–5	5–8	8–16	16–30	>30	
		Wheat	0–3	3–5	5–10	10–15	>15	
Depth, cm		Broad bean	0–3	3–5	5–10	10–15	>15	
		Maize	0–3	3–15	15–35	35–55	>55	
Soil	CaCO ₃ , g kg ⁻¹	Wheat	L, CL, SC, C	SL, SCL	LS, SiL, SiCL	SiC, S, Si	Gravel content > 60%	
		Maize	L, SCL, SL	SiCL, SiL, Si, SC, CL, C < 60, LS	SiC, S	C > 60		
	Gypsum, g kg ⁻¹	Wheat	> 90	90–50	50–20	20–10	<10	
		Maize	> 100	100–75	75–50	50–20	<20	
	Broad bean	> 100	100–75	75–50	50–25	<25		
		30–200	200–300	300–400	400–600	> 600		
	Wheat	0–60	60–150	150–250	250–350	> 350		
		0–200	200–300	300–400	400–600	> 600		
	Maize	0–30	30–50	50–100	100–200	> 200		
		0–20	20–40	40–100	100–200	> 200		

Table 1 (continued)

Criteria	Sub-criteria	Crop	Class, rating scale and limitation degree				
			S1	S2	S3	N1	N2
pH		Broad bean	0-30	30-50	50-100	100-200	>200
		Wheat	7-7.5	7.5-8.2	8.2-8.3	8.3-8.5	>8.5
		Maize	6.6-7	7-7.8	7.8-8.2	8.2-8.5	>8.5
Organic carbon (OC), g kg ⁻¹		Broad bean	6.5-7	7-7.5	7.5-8	8-8.5	>8.5
		Wheat	>6	6-4	<4	--	--
		Maize	>8	8-4	<4	--	--
Electrical conductivity (EC), dS m ⁻¹		Broad bean	>17	17-12	12-9	<9	--
		Wheat	<4	4-8	8-10	10-16	>16
		Maize	<4	4-6	6-8	8-12	>12
Exchangeable sodium percentage (ESP)		Broad bean	<4	4-6	6-8	8-12	>12
		Wheat	0-15	15-20	20-35	35-45	>45
		Maize	0-8	8-15	15-20	20-25	>25
Irrigation water		Broad bean	0-8	8-15	15-20	20-25	>25
	pH	All	6.5-8.4	--	--	--	<6.5 or >8.4
	EC, dS m ⁻¹	Wheat	<4	4-4.9	4.9-6.3	6.3-8.7	>8.7
Sodium adsorption ratio (SAR)		Maize	<1.1	1.1-1.7	1.7-2.5	2.5-3.9	>3.9
		Broad bean	<1.1	1.1-1.8	1.8-2	2-4.5	>4.5
		Wheat	<3	3-6	6-12	12-20	>20
Na ⁺ , mg L ⁻¹		Maize	<3	3-6	6-12	12-20	>20
		Broad bean	<3	3-6	6-9	6-15	>15
		Wheat	<46	46-230	46-115	115-230	>230
Cl ⁻ , mg L ⁻¹		Maize	<46	46-230	46-115	115-230	>230
		Wheat	<142	142-350	--	--	>350
		Maize	<142	142-350	--	--	>350
NO ₃ -N		Broad bean	<142	142-350	350-1065	--	>1065
		All	<5	5-10	10-30	--	>30
	HCO ₃ ⁻ , mg L ⁻¹	Wheat	<92	92-520	--	--	>520
	Maize	<92	92-520	--	--	>520	

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N1, currently not suitable; N2, permanently not suitable; S, sand; LS, loamy sand; SL, sandy loam; L, loam; SiL, silt loam; Si, silt; SCL, sandy clay loam; CL, clay loam; SiCL, silty clay loam; SC, sandy clay; SiC, silty clay; C, clay

for the four major criteria based on the importance of one criterion over another with a rating scale of 1 to 9. The scale of 1 reflects equal importance, while 9 denotes absolute importance. The definitions used for the comparison are considered according to the criteria presented in Table 2. Similarly, PCMs ($n \times n$) were also established for the sub-criteria defining each major group. The relative importance of each factor depended on the opinions of twelve local agricultural experts through questionnaires in addition to the authors' experiences. Secondly, the AHP online system package was used for calculating the weight value for each factor. Finally, the reality of weights was tested based on the consistency ratio (CR). The CR is calculated using the consistency index (CI) and random consistency index (RI) as follows:

$$CR = CI/RI$$

The CI is calculated using the maximum eigenvalue for each PCM (λ_{\max}) and the number of criteria (n) as follows:

$$CI = (\lambda_{\max} - n)/(n - 1)$$

The RI values are differed according to the number of analyzed criteria as shown in Table 3.

According to Saaty (2008), the PCM with CR lesser than 0.10 (10%) was considered to be valid, while that of higher values was revised. To ensure high accuracy, the AHP was applied two times through considering the arithmetic and geometric mean algorithms of the expert suggestions. The method with low CR was taken into account.

The soil attributes (coarse fragments, sand, silt, clay, pH, EC, OC, ESP, CaCO₃, and gypsum) of each horizon were recalculated based on profile depth and weighting factors suggested by Sys et al. (1991). This provided a representative one value for the whole profile. Using ArcGIS 10.8, the slope map is subjected to zonal statistics to obtain a mean value for each mapping unit and reclassified based on Table 1. Vector layers for climate, soil, and groundwater attributes were generated, converted to raster format using polygon to raster conversion technique, and reclassified (Table 1). Climate, soil and irrigation water suitability maps were generated using the weighted overlay (WO) analysis based on weights derived from AHP. The final crop suitability maps were developed by integrating the reclassified layers of the major criteria with their AHP weights using the WO technique.

Results

Geomorphology and soils

As shown in Fig. 5 and Table 4, eolian and alluvial plains are the major landscapes in the studied area. The eolian

Table 2 The analytical hierarchical process (AHP) evaluation scale (Saaty, 2008)

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2 – 4 – 6 – 8	Intermediate values

plain occupies 905.15 km², representing 72.03% of the total area. This landscape includes three landforms: high, moderate, and low sand sheets that account for 41.11, 16.21, and 14.72% of the total area, respectively. The soils of this landscape belong to the Entisols order and are classified as Typic Torripsamments. The alluvial plain landscape occupies 351.54 km² that accounts for 27.97% of the total area. This landscape includes a series of terraces, i.e., high, moderately high, moderate, and low that accounted for 3.34, 5.0, 7.51, and 12.12% of the total area, respectively. The main soils of this landscape belong to two orders, i.e., Aridisols and Entisols. The Aridisols are classified as Sodic Haplocalcids, while the Entisols are classified as Typic Torriorthents.

Characteristics of soils and groundwater

As shown in Table 5, the soils in all mapping units were very deep (> 150 cm), except soils of AP 113 unit that had a depth of 70 cm (moderately deep). The coarse fragment content varied from very few (1.55%) to abundant (50.32%) (FAO 2006). The ranges of CaCO₃ and gypsum contents were 74.64 to 258.13 g kg⁻¹ for the former and 3.03 to 29.34 g kg⁻¹ for the latter. This indicates that the soils were moderately to extremely calcareous and slightly gypsiferous (FAO 2006). The ranges of pH (6.77 to 9.50) and EC (0.95 to 24.60 dS m⁻¹) show that the soils were neutral to strongly alkaline and non-saline to strongly saline (Soil Science Division Staff 2017). The soils had extremely low OC (< 3 g kg⁻¹) and a very low to low CEC (3.89 to 8.95 cmol_c kg⁻¹) (Hazelton and Murphy 2016). The ESP range (11.16 to 61.48) indicates non to very high sodicity hazards (Abrol et al. 1988). The sand dominated soil particle size distribution with an average of 82.97% flowed by silt (11.42%) and clay (5.61%). Loamy sand, sand, and sandy loam were the predominant soil textural classes, representing 64, 29, and 7% of the total samples, respectively.

Results in Table 6 show that groundwater samples had pH values within the normal range for irrigation (6.5–8.4) as set by FAO 29 guidelines (Ayers and Westcott 1994), except sample of well no. 3. The EC range (0.64 to 3.49 dS m⁻¹) indicates none to severe salinity risks. Using the EC and

Table 3 The number of criteria (*n*) and the corresponding random consistency index (RI) values

<i>n</i>	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51	1.52	1.54	1.56

Fig. 5 Map of geomorphic units in the studied area

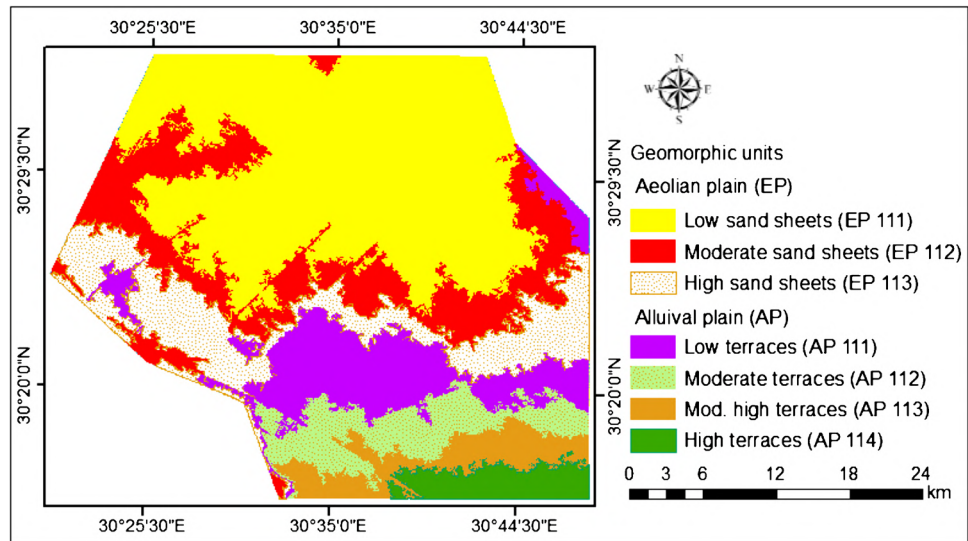


Table 4 Geomorphic units and soil taxonomy in the studied area

Landscape	Relief	Lithology	landform	Unit	Main soil	Area km ²	%
Eolian plain (EP)	Sand sheets (1)	Quaternary sand deposits (1)	Low (1)	EP 111	Typic Torripsamments	516.56	41.11
			Moderate (2)	EP 112		203.68	16.21
			High (3)	EP 113		184.91	14.72
Alluvial plain (AP)	Series of terraces (1)	Pliocene formation, Alluvial-Colluvial deposits (1)	Low (1)	AP 111	Sodic Haplocalcids, 67% Typic Torriorthents, 33%	152.26	12.12
			Moderate (2)	AP 112	Sodic Haplocalcids	94.38	7.51
			Mod. high (3)	AP 113	Sodic Haplocalcids	62.82	5.00
			High (4)	AP 114	Sodic Haplocalcids	41.99	3.34

SAR together, the groundwater had no restriction in use concerning potential infiltration problems, except wells no. 3 and 6 that had slight to moderate restrictions. Regarding toxicity problems from the root intake, the SAR values for all water samples indicate slight to hazards, except samples of well no. 3 that had no restrictions. However, the concentrations of Cl⁻ indicate no (well no. 3 and 6), slight to moderate (wells 9 and 10), and sever risks (the remaining samples). On the other hand, the concentrations of Na⁺ and Cl⁻ in all water samples point to slight to moderate risks from the root intake, except sample of well 3 that had no restrictions. Slight to moderate NO₃-N problems were detected in three water samples, i.e., wells 2, 4, and 7, while the remaining samples showed no hazards. All water samples had slight to moderate restrictions concerning HCO₃⁻ hazards, except

samples of wells 4 and 9 that had no limitations. The concentrations of Ca²⁺, Mg²⁺, and SO₄²⁻ in all water samples were within the FAO standard limits of 400, 60, and 960 mg L⁻¹, respectively. Moreover, the concentrations of PO₄-P in all samples did not surpass the normal range for irrigation water (< 2 mg L⁻¹), except sample of well 8.

Crop suitability evaluation

The AHP criteria and sub-criteria involved in suitability analyses are presented in Table 7. The weights derived from the AHP show that minimum temperature was the most effective criterion for climate suitability for wheat and broad bean followed mean temperature, while maximum one had the lowest impact. On the other hand, for maize, the highest

Table 5 Physicochemical properties of the studied soil profiles

Unit	Profile	Depth, cm	CF, %	pH	EC, dS m ⁻¹	CaCO ₃ , g kg ⁻¹	Gypsum, g kg ⁻¹	OC, g kg ⁻¹	CEC, cmol _c kg ⁻¹	ESP	Particle size distribution, %		Textural class	
											Sand	Silt		Clay
EP 111	11	0–30	5.41	7.19	9.70	108.85	23.76	0.47	4.71	45.52	86.91	7.44	5.65	Sand
		30–150	5.11	7.31	4.95	108.85	20.77	0.35	4.53	44.23	86.28	8.18	5.54	Sand
	12	0–25	2.41	7.36	4.60	105.74	18.21	2.56	4.41	40.05	85.94	8.61	5.45	Sand
		25–150	1.55	7.28	1.35	90.19	26.35	0.29	4.82	11.16	86.78	7.57	5.65	Sand
	13	0–20	5.14	7.22	1.10	133.73	17.31	0.35	6.91	13.41	83.52	11.15	5.33	Loamy sand
EP 112	14	20–60	10.21	7.10	1.35	143.06	13.03	1.51	7.13	14.97	84.61	9.83	5.56	Loamy sand
		60–150	50.13	7.31	1.35	102.63	24.62	0.41	4.62	12.88	86.59	7.85	5.56	Sand
	9	0–30	10.11	7.41	21.95	90.19	20.37	0.23	7.07	51.10	83.76	10.93	5.31	Loamy sand
		30–80	10.22	7.21	10.95	124.40	18.61	0.47	7.21	37.67	81.63	13.06	5.31	Loamy sand
	10	80–150	5.14	7.01	7.95	99.52	25.05	0.52	4.52	36.69	86.55	7.92	5.53	Sand
EP 113	5	0–20	20.36	7.66	23.50	258.13	3.03	0.17	8.95	55.54	83.88	10.80	5.32	Loamy sand
		20–50	5.14	7.74	10.25	161.72	13.43	0.41	6.93	40.43	83.92	10.62	5.46	Loamy sand
	10	50–150	5.10	6.88	9.80	152.39	11.73	0.23	6.44	39.88	84.67	9.92	5.41	Loamy sand
		0–30	10.10	7.00	4.85	155.50	20.27	0.17	6.31	39.09	82.97	11.58	5.45	Loamy sand
	15	30–90	5.11	6.96	2.90	167.94	15.56	0.52	7.12	29.25	82.34	12.38	5.28	Loamy sand
AP 111	3	90–150	10.62	7.12	0.95	102.63	27.61	0.41	4.14	12.09	86.37	8.15	5.48	Sand
		0–20	15.10	6.95	11.00	115.07	25.89	0.35	6.93	34.71	82.48	12.10	5.42	Loamy sand
	7	20–60	15.30	6.77	11.15	164.83	15.99	0.23	6.71	34.93	83.52	11.12	5.36	Loamy sand
		60–150	10.11	6.87	10.50	174.16	11.70	0.41	6.62	34.76	83.66	11.03	5.31	Loamy sand
	8	0–20	20.11	8.48	5.40	177.27	17.25	0.47	5.91	39.64	83.71	10.84	5.45	Loamy sand
AP 113	5	20–70	15.32	8.56	2.40	87.08	23.79	0.29	6.74	24.87	83.57	11.07	5.36	Loamy sand
		70–150	10.63	8.75	1.40	102.63	18.64	0.12	6.37	17.82	82.95	11.79	5.26	Loamy sand
	7	0–20	4.23	8.04	10.25	152.39	14.72	0.47	6.91	36.29	84.00	10.61	5.39	Loamy sand
		20–80	4.11	8.12	7.20	99.52	25.05	0.41	4.22	25.76	86.57	7.94	5.49	Sand
	3	80–150	10.22	8.18	10.80	90.19	29.34	0.23	3.89	40.15	86.90	7.45	5.65	Sand
AP 111	3	0–30	20.36	8.55	9.60	149.28	15.75	0.47	7.13	37.29	81.86	12.91	5.23	Loamy sand
		30–70	10.10	8.57	7.80	161.72	25.39	0.52	6.45	32.02	82.90	11.66	5.44	Loamy sand
	4	70–150	15.20	8.69	4.40	100.40	21.60	0.23	6.91	27.71	81.64	13.12	5.24	Loamy sand
		0–20	5.32	8.13	24.60	74.64	22.53	0.19	6.64	61.48	72.96	19.41	7.63	Sandy loam
	8	20–50	15.32	8.43	9.40	74.64	25.22	0.17	7.23	38.68	82.73	11.89	5.38	Loamy sand
AP 111	8	50–150	45.32	8.63	2.65	96.41	25.49	0.11	4.34	23.39	86.89	7.56	5.55	Sand
		0–20	10.11	8.09	10.65	136.84	16.88	0.35	6.67	40.20	79.38	15.55	5.07	Loamy sand
	20–60	20.11	7.08	15.00	164.83	10.01	0.29	7.24	38.46	78.89	15.93	5.18	Loamy sand	
AP 111	8	60–150	10.36	7.24	12.70	189.71	15.52	0.47	6.73	45.64	81.61	13.15	5.24	Loamy sand

Table 5 (continued)

Unit	Profile	Depth, cm	CF, %	pH	EC, dS m ⁻¹	CaCO ₃ , g kg ⁻¹	Gypsum, g kg ⁻¹	OC, g kg ⁻¹	CEC, cmol _c kg ⁻¹	ESP	Particle size distribution, %			Textural class
											Sand	Silt	Clay	
AP 112	6	0–20	40.55	8.15	11.00	169.28	18.15	0.52	7.07	45.97	79.38	15.41	5.21	Loamy sand
		20–55	40.60	8.71	1.55	93.30	28.91	0.35	4.13	17.70	87.11	7.33	5.56	Sand
AP 113	2	55–150	40.11	8.87	1.10	87.08	20.80	0.23	4.51	15.36	86.59	7.72	5.69	Sand
		0–15	15.23	8.82	19.45	258.80	13.30	0.35	8.72	56.11	73.82	18.23	7.95	Sandy loam
AP 114	1	15–70	10.62	9.23	1.30	191.92	7.78	0.41	6.84	18.55	80.21	14.57	5.22	Loamy sand
		0–30	30.11	8.47	13.20	223.92	4.79	0.41	8.91	46.55	72.91	18.46	8.63	Sandy loam
		30–90	50.32	8.48	7.95	199.04	11.24	0.29	6.14	33.64	80.01	13.64	6.35	Loamy sand
		90–150	10.62	9.50	2.50	74.64	27.01	0.47	6.63	21.52	81.57	13.19	5.24	Loamy sand

CF, coarse fragments; EC, electrical conductivity; OC, organic carbon; CEC, cation exchange capacity; ESP, exchangeable sodium percentage

priority was assigned to maximum temperature followed by mean and minimum temperature. However, results of climate suitability analysis (Table 8) indicated that 100% of the studied area would be in the S1 class for the three crops. On the other hand, in terms of topographic suitability, results in Table 8 show that 100% of the studied area would be in the S2 class for wheat and maize cultivation under sprinkler irrigation while in the S1 class for broad bean cropping under drip irrigation.

The AHP indicated that soil properties showed varied effects on soil suitability according to crop type. However, EC, ESP, and CaCO₃ were the most important properties affecting soil suitability for the three crops. The soil suitability maps (Fig. 6) reveal that the studied area would occur in three suitability classes for wheat (S1, S2, and S3) but in two classes (S2 and S3) for maize and broad bean cultivations. The suitability analyses (Table 8) indicate that 41, 22, and 37% of the total area were found in S1, S2, and S3 classes for wheat, respectively. Under maize and broad bean cultivations, areas of S2 and S3 classes were found in 63 and 37% of the total area, respectively.

Water quality parameters showed also varied contributions to groundwater suitability under each irrigation method. However, for the two irrigation systems, EC and pH had the highest and lowest impacts, respectively. As shown in Fig. 7, groundwater in the studied area would be in three classes, i.e., S1, S2, and S3 for wheat and broad bean, while in S1, S2, and S4 for maize irrigation. Results in Table 8 show that groundwater in 15, 21, and 64% of the studied area occurred in S1, S2, and S3 classes for wheat irrigation, respectively. Furthermore, groundwater in 15, 21, and 64% of the area fitted S1, S2, and N1 classes for maize irrigation, respectively. Under broad bean irrigation, groundwater in 20, 16, and 64% of the area belonged to S1, S2, and S3 classes, respectively.

The pairwise comparison matrix of the four main suitability criteria (Table 7) revealed that irrigation water quality had the highest specific weight (0.38) followed by soil (0.36) and topography (0.15), while climate conditions had the lowest influence (0.10). The crop suitability maps presented in Fig. 8 show that the studied area would be in the S2 and S3 classes for the selected crops; however, these classes covered different areas as presented in Table 8. The S2 class for wheat covered 97% of the total area (121,461 ha), while the S3 class covered only 3% (41,99 ha). For maize production, the S3 dominated 64% of the total area (805,19 ha), while the remaining 36% (45,141 ha) fitted the S2 class. The S2 class for broad bean occurred in 85% of the total area (106,235 ha), while only 15% (19,425 ha) occurred in the S3 class.

Table 6 Chemical composition of the studied groundwater samples

Well no	pH	EC, dS m ⁻¹	SAR	Soluble ions, mg L ⁻¹								
				Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	NO ₃ ⁻	HCO ₃ ⁻	PO ₄ ³⁻	SO ₄ ²⁻
1	8.05	2.15	7.94	128.11	31.68	388.11	9.39	570.52	<0.02	181.11	0.22	288.82
2	8.11	3.23	8.93	191.21	28.45	501.31	7.37	743.13	6.17	142.33	1.03	448.11
3	8.39	0.64	2.27	54.31	11.57	70.79	5.40	102.33	1.11	109.82	0.59	60.97
4	7.94	3.49	8.25	233.44	21.26	492.17	6.42	758.42	18.35	78.42	1.29	541.21
5	7.97	2.61	6.38	195.24	20.43	351.22	7.72	535.53	3.87	92.16	1.78	447.61
6	7.91	0.76	3.19	46.27	12.63	95.16	5.16	136.47	<0.02	107.41	0.73	88.78
7	7.73	2.67	8.42	147.40	20.39	412.56	5.71	610.94	8.98	170.23	0.38	316.69
8	7.68	2.72	8.63	151.13	19.91	426.11	6.63	631.54	2.23	175.31	2.33	321.93
9	7.79	1.11	6.87	43.49	9.29	191.81	4.52	268.72	<0.02	88.83	<0.02	85.89
10	8.15	1.36	6.89	50.93	15.64	219.77	5.95	305.53	0.39	214.21	<0.02	62.22

EC, electrical conductivity; SAR, sodium adsorption ratio

Discussion

Geomorphology and soils

Integrating remote sensing data and GIS tools is the most common approach applied to generate geomorphic maps at different scales (Obi Reddy 2018). Interpreting satellite imageries and DEM in conjunction with field surveys allows the segmentation of landscapes into homogeneous units for which soil composition can be identified through sampling (Srivastava 2018). This makes land resources assessment at regional scales more simple, time-saving, and cost-effective compared with intensive field surveys (Abuzaid et al. 2021a). In the studied area, major landscapes are formed due to interactions of alluvial and eolian processes. The former occurs when water movement is available, while the latter dominates when water becomes more limited (Elbasiouny and Elbehiry 2019). The eolian process is predominant, and thus, sand landforms (sand sheets) cover the majority of the area (72%). The sedimentation of the Palaeo-fluvial deposits during fluvial periods formed alluvial landforms (terraces) in small parts (Hamdan and Hassan 2020). The aridity conditions resulted in low soil profile development due to a lack of active pedological processes (Soil Survey Staff 2014a). Hence, young soils (Entisols) formed on sandstones (Torripsamments) and siltstones and sandstones (Torriorthents) dominated the studied area, while more-developed soils (Aridisols) formed on limestone (Haplocalides) occurred in a small portion.

Characteristics of soils and groundwater

The studied soils showed physicochemical properties typical for arid and desert environments, which have been indicated in previous studies (Jafari et al. 2018; Osman 2018a; Shokr et al. 2021). Under these environment, the characteristics of

soil profile are primarily affected by geological formations and climate conditions (Fadl et al. 2022). The dryland soils are likely affected by the major climatic events occurred during the Quaternary ear, when fluctuations of arid and humid conditions were accompanied by active eolian processes and carbonate accumulation (de-Bashan et al. 2022). Moreover, due to aridity conditions, the physical weathering of soil parent materials through thermal fluctuations related to diurnal heating and cooling is the prevailing soil-forming process (Lopez and Bacilio 2020). As a result, the soils are usually dominated by coarse fractions and rock fragments that have positive effects on drainage conditions but negative effects on the exchange capacity (Abdellatif and Abuzaid 2021). The combined effect of soil bedrocks and aridity conditions is evident also on other chemical properties (Osman 2018a). Excessive CaCO₃ and Na₂CO₃ might increase the soil pH values through the production of OH⁻ during hydrolysis (Jafari et al. 2018). In addition, the predominance of sodium carbonate and bicarbonate salts might cause high ESP values (Osman 2018b). The limited rainfall and high evaporation rates diminish the deep leaching of soluble salt, CaCO₃, and gypsum, and thus, they accumulate in soils (Abuzaid et al. 2021b). The sparse vegetation cover and low biomass production led to low OC in soils (Abuzaid and Fadl 2016).

The water composition specifies the suitability of any water body for a definite use and summarizes water quality dynamics and controlling mechanisms (Abuzaid and Jahin 2022). The groundwater composition in the studied area points to mutual effects of water-bearing formations and agricultural activities. This hypothesis has been affirmed in previous studies in the west Nile Delta region (Masoud 2014; Eltarabily and Negm 2019). The dissolution of carbonate minerals (calcite and dolomite) might increase the concentrations of HCO₃⁻ that raised the pH (Salem and Osman 2017). Consequently, the high influx of HCO₃⁻ increases SAR values due to precipitation of Ca²⁺

Table 7 Comparison matrixes and weights of criteria used for crop suitability evaluation

Criteria	Pairwise comparison matrix									Rank	Weight	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)			
Major suitability criteria												
(1) Climate	1	1	1/4	1/5							4	0.104
(2) Topography	1	1	1/2	1/2							3	0.154
(3) Soil	4	2	1	1							2	0.358
(4) Irrigation water	5	2	1	1							1	0.384
$\lambda_{max} = 4.087, n = 4, CI = 0.029, RI = 0.9, CR (CI/RI) = 0.032$											Sum	1.000
Climate criteria for wheat and broad bean												
(1) Min temperature	1	7	3								1	0.681
(2) Max temperature	1/7	1	1/2								3	0.103
(3) Mean temperature	1/3	2	1								2	0.216
$\lambda_{max} = 3.003, n = 3, CI = 0.002, RI = 0.58, CR (CI/RI) = 0.003$											Sum	1.000
Climate criteria for maize												
(1) Min temp	1	1/7	1/3								1	0.681
(2) Max temp	7	1	2								3	0.103
(3) Mean temp	3	1/2	1								2	0.216
$\lambda_{max} = 3.003, n = 3, CI = 0.002, RI = 0.58, CR (CI/RI) = 0.003$											Sum	1.000
Soil criteria for wheat												
(1) Coarse fragments	1	3	3	3	3	4	4	1/4	3	2	0.190	
(2) Texture	1/3	1	3	1/4	1	1	4	1/5	1/5	6	0.057	
(3) Depth	1/3	1/3	1	1/4	1/5	1/3	1	1/9	1/4	9	0.027	
(4) CaCO ₃	1/3	4	4	1	3	3	3	1/3	1/3	4	0.112	
(5) Gypsum	1/3	1	5	1/3	1	3	4	1/4	1/4	5	0.075	
(6) pH	1/4	1	3	1/3	1/3	1	2	1/4	1/4	7	0.047	
(7) OC	1/4	1/4	1	1/3	1/4	1/2	1	1/5	1/4	8	0.030	
(8) EC	4	5	9	3	4	4	5	1	2	1	0.290	
(9) ESP	1/3	5	4	3	4	4	4	1/2	1	3	0.172	
$\lambda_{max} = 9.988, n = 9, CI = 0.124, RI = 1.45, CR (CI/RI) = 0.085$											Sum	1.000
Soil criteria for maize												
(1) Coarse fragments	1	1/3	1	1/3	1/3	1/4	1	1/4	1/7	4	0.108	
(2) Texture	3	1	3	1/5	1	1	4	1/5	1/5	6	0.056	
(3) Depth	1	1/3	1	1/5	1/4	1/3	1	1/9	1/4	8	0.031	
(4) CaCO ₃	3	5	5	1	3	3	3	1/3	1/3	3	0.144	
(5) Gypsum	3	1	4	1/3	1	3	4	1/4	1/4	5	0.076	
(6) pH	4	1	3	1/3	1/3	1	3	1/4	1/4	7	0.048	
(7) OC	1	1/4	1	1/3	1/4	1/3	1	1/5	1/4	9	0.029	
(8) EC	4	5	9	3	4	4	5	1	1	1	0.286	
(9) ESP	7	5	4	3	4	4	4	1	1	2	0.222	
$\lambda_{max} = 10.023, n = 9, CI = 0.128, RI = 1.45, CR (CI/RI) = 0.088$											Sum	1.000
Soil criteria for broad bean												
(1) Coarse fragments	1	1/3	1	1/3	1/3	1/4	1	1/4	1/7	8	0.033	
(2) Texture	3	1	3	1/5	1	1	4	1/5	1/5	5	0.071	
(3) Depth	1	1/3	1	1/5	1/4	1/3	1	1/9	1/4	9	0.030	
(4) CaCO ₃	3	5	5	1	3	3	3	1/3	1/3	3	0.155	
(5) Gypsum	3	1	4	1/3	1	3	4	1/4	1/4	4	0.093	
(6) pH	4	1	3	1/3	1/3	1	3	1/4	1/4	6	0.069	
(7) OC	1	1/4	1	1/3	1/4	1/3	1	1/5	1/4	7	0.034	
(8) EC	4	5	9	3	4	4	5	1	1	1	0.262	
(9) ESP	7	5	4	3	4	4	4	1	1	2	0.253	

Table 7 (continued)

Criteria	Pairwise comparison matrix									Rank	Weight	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)			
$\lambda_{\max} = 9.744, n = 9, CI = 0.093, RI = 1.45, CR (CI/RI) = 0.064$										Sum	1.000	
Water quality criteria for sprinkler irrigation												
(1) pH	1	1/4	1/3	1/4	1/4	1/2	1/3				7	0.041
(2) EC	4	1	4	2	2	4	4				1	0.294
(3) SAR	3	1/4	1	1/4	1/4	1/3	1/3				6	0.055
(4) Na ⁺	4	1/2	4	1	2	4	4				2	0.243
(5) Cl ⁻	4	1/2	4	1/2	1	4	4				3	0.200
(6) NO ₃ -N	2	1/4	3	1/4	1/4	1	1/2				5	0.073
(7) HCO ₃ ⁻	3	1/4	3	1/4	1/4	2	1				4	0.094
$\lambda_{\max} = 7.585, n = 7, CI = 0.089, RI = 1.32, CR (CI/RI) = 0.074$										Sum	1.000	
Water quality criteria for drip irrigation												
(1) pH	1	1/4	1/5	1/4	1/2				5	0.057		
(2) EC	4	1	2	2	5				1	0.382		
(3) SAR	5	1/2	1	3	4				2	0.312		
(4) Cl ⁻	4	1/2	1/3	1	2				3	0.165		
(5) NO ₃ -N	2	1/5	1/4	1/2	1				4	0.084		
$\lambda_{\max} = 5.196, n = 5, CI = 0.049, RI = 1.12, CR (CI/RI) = 0.044$										Sum	1.000	

and Mg²⁺, leaving Na⁺ as the predominant cation (Abbas et al. 2020). Both Na⁺ and Cl⁻ are major ions for groundwater in arid and semi-arid regions (Su et al. 2020; Marghade et al. 2021). They are derived from agricultural activities and natural sources, i.e., weathering of feldspar minerals (Na⁺) and dissolution of halite (Cl⁻) (Su et al. 2020). Moreover, the dissolution of evaporite minerals (gypsum and anhydrite) might contribute to Ca²⁺ and SO₄²⁻ (Masoud 2014). On the other hand, nutrient leaching from the cultivated fields might supply the groundwater in some localities with NO₃-N and PO₄-P (El Maghraby et al. 2014). The groundwater salinity, in turn, increased due to high concentrations of soluble ions.

Crop suitability evaluation

Crop suitability analysis, in general, can devote the natural resources to the proper land-use pattern (Fadl and Abuzaid 2017) and also suggest the required management practices to obtain the optimum crop yield (Loiskandl and Nolz 2021). Hence, crop-based land suitability models through matching ecologic requirements of plants with local area conditions are important for precision farming and sustainable crop production (Everest et al. 2021a; Everest and Gür, 2022). The crop requirements concerning climate, landscape, and soil conditions for a wide range of field crops have been suggested by Sys et al. (1993). However, locally related standards available through official sources and expert knowledge should be taken into account (Kalogirou 2002; Everest et al. 2021b). In addition, irrigation water availability with proper quality is of great concern for sustainable crop production

(Loiskandl and Nolz 2021). Thus, combining these requirements with their relative importance based on local experiences would render the suitability modeling more realistic and useful (Everest and Gür 2022).

Under irrigated agriculture, especially in arid and semi-arid regions, climate suitability for crop production is affected mainly by minimum, mean, and maximum temperature during the growing season (Tashayo et al. 2020a, b). The temperature has direct effects on the physicochemical reactions of the plants and thus affects the rate of development and biomass production (Ali 2010). These parameters are expected to gain more attention due global warming related to accelerated climate change (Everest et al. 2021a). Other factors related to crop evapotranspiration (solar radiation, humidity, wind speed, and sunshine hours) are regulated through irrigation scheduling (Ali 2010) and effective agricultural practices (Everest and Gür, 2022). The analyses of climate data indicated that air temperature in the studied area would fulfill the optimum growth requirements for the selected crops. Osman (2018a) and Jafari et al. (2018) reported that wheat, maize, and broad bean are the most suitable food crops for arid and desert ecosystems.

The slope gradient has an important role in land suitability for crop production since it determines irrigation type, rate of drainage, and potential use of mechanization during management practices (Everest and Gür, 2022). This is in addition to indirect effects on soil development and crop yield (Tashayo et al. 2020a). The slope gradient in the studied area would pose slight limitations for wheat and maize cropping under sprinkler irrigation but no limitations for

Table 8 Distribution of crop suitability classes in the studied area

Factor	Crop	Area	Class				
			S1	S2	S3	N1	N2
Climate	Wheat	km ²	1256.60	—	—	—	—
		%	100.00	—	—	—	—
	Maize	km ²	1256.60	—	—	—	—
		%	100.00	—	—	—	—
	Broad bean	km ²	1256.60	—	—	—	—
		%	100.00	—	—	—	—
Topography	Wheat	km ²	—	1256.60	—	—	—
		%	—	100.00	—	—	—
	Maize	km ²	—	1256.60	—	—	—
		%	—	100.00	—	—	—
	Broad bean	km ²	1256.60	—	—	—	—
		%	100.00	—	—	—	—
Soil quality	Wheat	km ²	516.56	279.29	460.75	—	—
		%	41.11	22.23	36.67	—	—
	Maize	km ²	—	795.85	460.75	—	—
		%	—	63.33	36.67	—	—
	Broad bean	km ²	—	795.85	460.75	—	—
		%	—	63.33	36.67	—	—
Water quality	Wheat	km ²	184.91	266.50	805.19	—	—
		%	14.71	21.21	64.08	—	—
	Maize	km ²	184.91	266.50	—	805.19	—
		%	14.71	21.21	—	64.08	—
	Broad bean	km ²	247.73	203.68	805.19	—	—
		%	19.71	16.21	64.08	—	—
Overall suitability	Wheat	km ²	—	1214.61	41.99	—	—
		%	—	96.66	3.34	—	—
	Maize	km ²	—	451.41	805.19	—	—
		%	—	35.92	64.08	—	—
	Broad bean	km ²	—	1062.35	194.25	—	—
		%	—	84.54	15.46	—	—

S1, highly suitable; S2, moderately suitable; S3, marginally suitable; N1, currently not-suitable; N2, permanently not-suitable

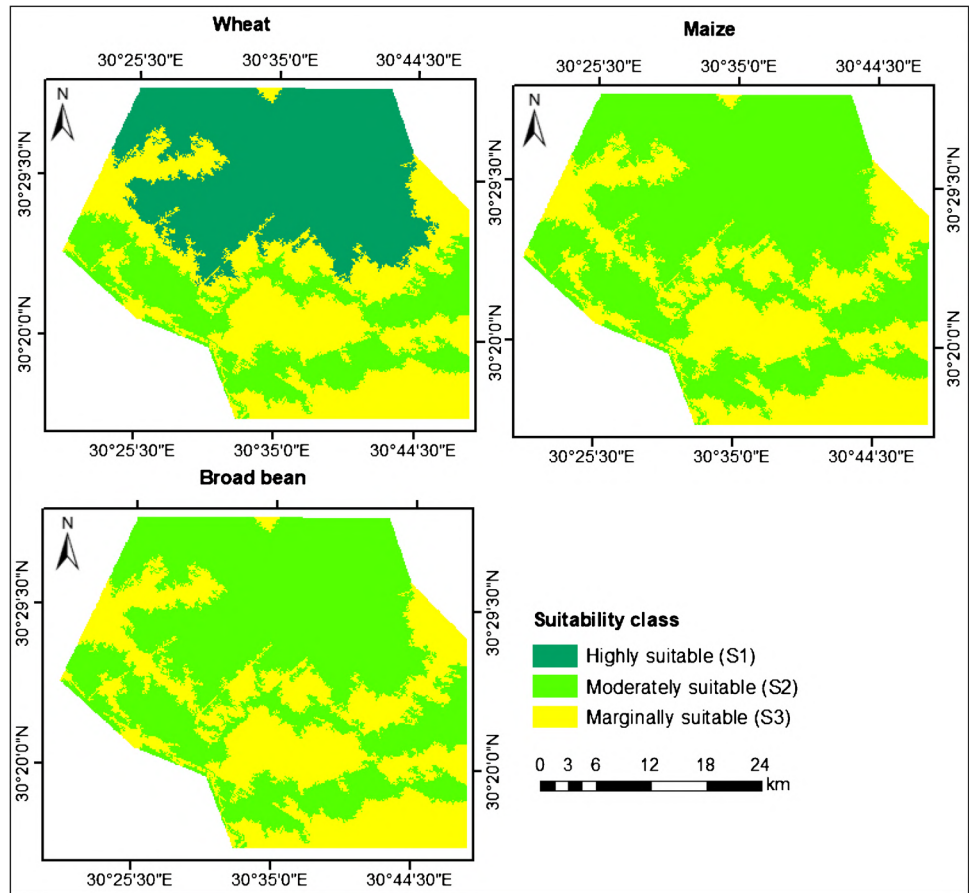
broad bean under drip irrigation (Mihalikova and Dengiz 2019). Using sprinkler irrigation in sloping lands increases the risks of soil runoff and erosion (Reddy 2016). Therefore, it is recommended to reduce the sprinkler flow rate, especially at the early stages of crop growing periods. Moreover, designing the riser orientation perpendicular to the slope would achieve good water application uniformity and infiltration rate (Hui et al. 2021).

The physicochemical properties of soil profiles determine soil suitability for crop production (Sys et al. 1993; Everest and Gür, 2022). Implications of these properties on soil functions govern its suitability for specific use (Dedeoglu and Dengiz 2019). The AHP provided in this study shows that EC, ESP, and CaCO₃ had the greatest impacts on soil suitability for broad bean, and these properties besides coarse fragments controlled soil suitability for wheat and

maize. The weight of each criterion is related to local area conditions and expert judgments. Crop suitability models using AHP for maize (Tashayo et al. 2020a) and fuzzy-AHP for wheat (Tashayo et al. 2020b) have been developed for saline, sodic, and calcareous soils of Iran. The most effective soil property was texture followed by pH, EC, and ESP, while CaCO₃ had the least impact. Moreover, AHP applied in modeling wheat suitability for saline calcareous soils of Egypt (Mohamed et al. 2019) showed that soil depth had the highest influence.

Salinity, sodicity, and lime are major threats for sustainable crop production in dryland ecosystems (Jafari et al. 2018; Abuzaid and Abdelatif 2022). Plants grown on salt-affected soils (saline, sodic, or saline-sodic) suffer from low water availability, nutrient deficiency, nutritional imbalances, and toxicity of specific ions (Na, Cl, B, Mo, and CO₃) (Jafari

Fig. 6 Soil suitability maps for wheat, maize, and broad bean



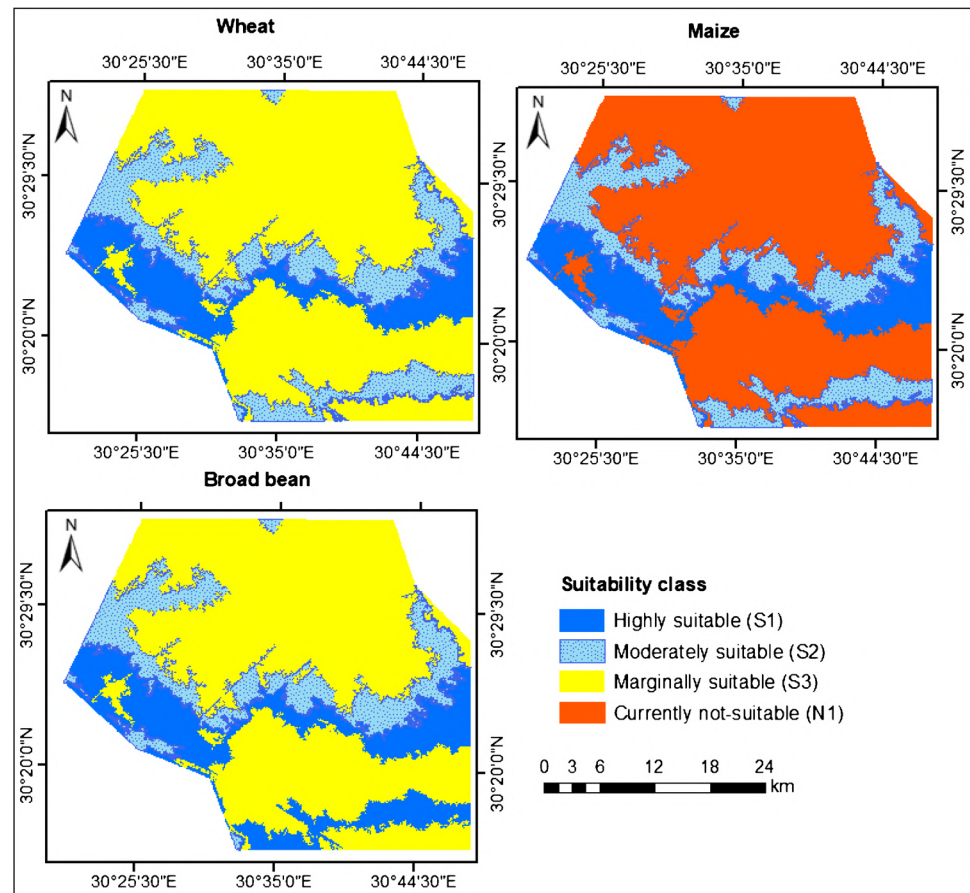
et al. 2018). These stresses adversely affect plant growth and lead to yield reduction based on the degree of crop resistance (Osman 2018b). The presence of CaCO_3 in saline-sodic soils may neutralize the negative effects of soluble and exchangeable Na^+ through the release of soluble Ca^{2+} (Jafari et al. 2018). This can modify the status of nutrient availability and increase soil permeability (Osman 2018b). However, excessive CaCO_3 leads to high nutritional problems mainly for N, P, Fe, and Zn elements (Wassif and Wassif 2021). The stoniness coupled with coarse texture adversely affects soil moisture storage (Mihalikova and Dengiz 2019). Furthermore, the gravel and stone-sized materials on the soil surface have negative effects on the soil tillage practices (Everest et al. 2021b).

Irrigation water quality plays a vital role in sustainable crop production as it is directly correlated with soil and plant ecosystems (Loiskandl and Nolz 2021). This relies on the sort and quantity of the soluble substances affecting soil and crop behaviors under a certain irrigation system (Jahin et al. 2020). The major problem categories related to irrigation water quality include salinity, infiltration, toxicity, and other miscellaneous effects (Abuzaid and Jahin 2022). Hence, in the present work, contributions of sub-criteria related these categories were considered to obtain a reliable evaluation

of groundwater suitability for irrigation. In this context, the AHP allocated the highest weights for EC and SAR under drip irrigation, while EC, Na^+ , and Cl^- under sprinkler irrigation. Using the AHP approach, salinity, infiltration, and toxicity problems were the major resections for groundwater irrigation in the Mediterranean basin such as in Turkey (Bozdağ, 2015) and Tunisia (Ncibi et al. 2020). Excessive salt renders the growing plants unable to uptake soil water owing to high osmotic potential (Zaman et al. 2018). Moreover, saline waters with high Na^+ or Cl^- cause a direct injury from leaf intake (Ayers and Westcot 1994). Groundwater salinity level in the studied area was highly suitable for wheat but had restrictions for maize and broad bean since wheat is more tolerant (Osman 2018b). The SAR has a dual effect regarding infiltration and toxicity problems (Zaman et al. 2018). The toxic ions Na^+ and Cl^- have more considerations under sprinkler irrigation as they directly accumulate in plant tissues through leaf absorption (Ayers and Westcot 1994). Hence, their potential toxicities pose higher threats for wheat and maize.

Quantifying impacts of the major criteria, the AHP indicated that irrigation water quality had the highest priority flowed by soil and topography, while climate had the lowest effect. Combinations of various suitability criteria and

Fig. 7 Irrigation water suitability maps for wheat, maize, and broad bean



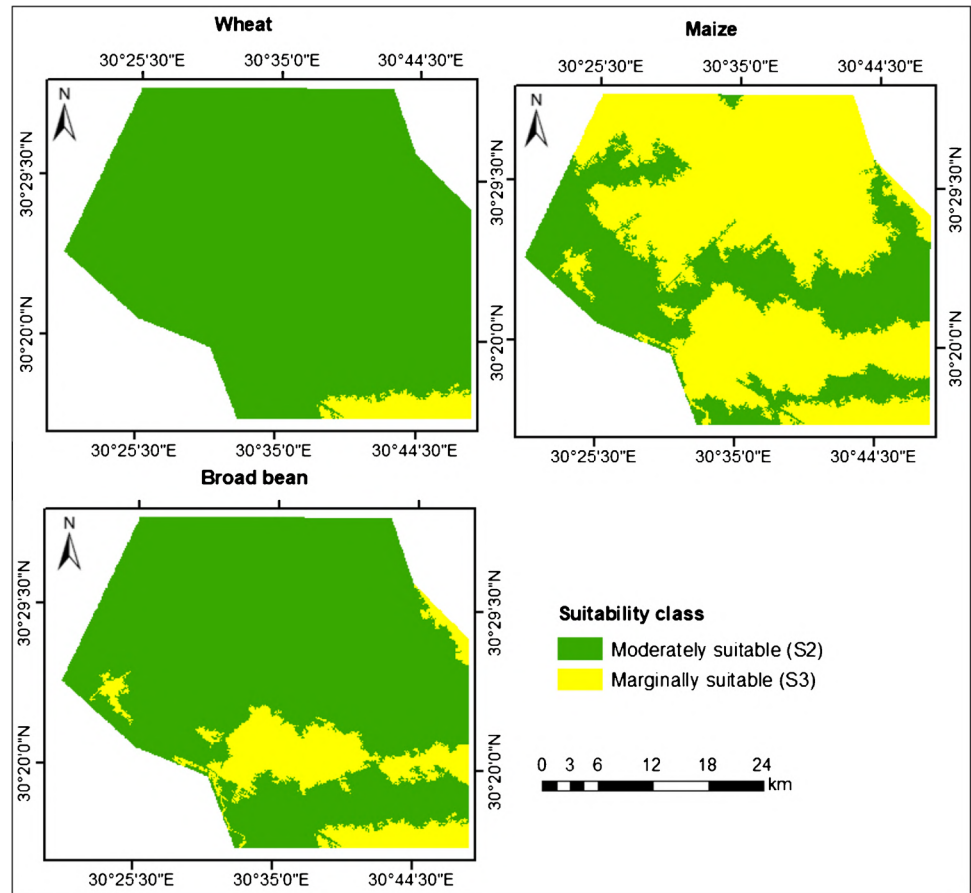
their relative importance in crop suitability models have been reported in previous cases studies on irrigated lands. Mohamed et al. (2019) confirmed the highest priority of soil properties over irrigation water salinity and slope factors in modeling land suitability for wheat. For maize and wheat production, Tashayo et al. (2020a) and Tashayo et al. (2020b) reported that soil factors were the most effective driver followed by topography and climate factors.

The combinations of the major criteria revealed that the studied area would be in the S2 and S3 classes for the three crops. These results are inconsistent with those obtained using the ALESarid-GIS model in the west Nile Delta region. Abd El-Kawy et al. (2010) reported that land suitability fell in S1, S2, and S3 classes for wheat, while in S3, S4, and N classes for maize and broad bean. Abd El-Kawy et al. (2019) indicated that areas of Wadi Al-Natron district fitted S2, S3, and S4 classes for wheat, while S2, S3, S4, and N classes for maize and broad bean. The ALESarid-GIS model assumes equal importance of the dominant characteristics (climate, soil, and water) affecting crops. However, GIS-MCDA applied in our work employed AHP through experts' judgments to specify the influence degree of these criteria. This, in turn, might provide a real estimation and improve the suitability analysis, resulting in significant

increases in the cultivated areas (Everest et al. 2021b; Everest and Gür, 2022).

Generally, site suitability for crop production is a function of the intensity of limitations affecting crop performance (Everest et al. 2021a). Land units with no and slight limitations exhibit higher fitness than those having moderate, severe, or very severe ones (Sys et al. 1991; Everest et al. 2021b). The prevailing conditions in all mapping units (except AP 114) fitted the S2 class for wheat. These units had slight slope limitations and slight to moderate limitations related to soil and irrigation. Besides slope, the AP 114 unit was affected by moderate soil and irrigation limitations, rendering it in the S3 class. For maize, three units (AP 113, EP 112, and EP 113) fitted the S2 class, where slight slope and irrigation and slight to moderate soil limitations occurred. The remaining units fell in the S3 class as they were affected by further limitations related to slope (slight), soil (slight to moderate), and irrigation (slight to severe). With exception of two units (AP 111 and AP 114), slight to moderate soil and irrigation limitations rendered the area in the S2 class for broad bean. On the other hand, moderate soil and irrigation limitations occurred in AP 111 and AP 114 units, and thus they fell in the S3 class.

Fig. 8 Crop suitability maps for wheat, maize and broad bean



Conclusion

The GIS-based modeling and AHP were applied as MCDA tools to generate suitability maps for cultivating wheat and maize under sprinkler irrigation and broad bean under drip irrigation. The study was conducted in a newly developed arid area (125,660 ha) in the west Nile Delta of Egypt. The analyses focused on matching local characteristics of climate, landscape (topography and soil), and irrigation water quality with the crop requirements. The climate conditions fitted the optimum growth requirements for the selected crops, while slope gradient posed limitations for wheat and maize cropping. The most important properties controlling soil suitability were EC, ESP, and CaCO_3 for broad bean, while these properties besides the coarse fragments affected soil suitability for wheat and maize. The EC, Na^+ , and Cl^- were the most influential variables affecting groundwater suitability for sprinkler irrigation; meanwhile, EC and SAR had the greatest priority under drip irrigation. The irrigation water quality had the highest priority in modeling crop suitability followed by soil, topography, while climate had the lowest impact. The most suitable crop under the studied area condition was wheat, where 97 and 3% of the area fitted the S2 and S3 classes,

respectively. Broad bean ranked the second suitable crop as 85 and 15% of the area fitted the S2 and S3 classes, respectively. Only 36% of the total area occurred in the S2 class for maize, while the remaining area (64%) fitted the S3 class. Using satellite imageries and DEM in conjunction with field surveys are effective tools for land-use planning on a regional scale. The combined use of AHP and GIS-based modeling would provide a better estimation of how locally dominant conditions affect crop suitability. Our findings would be a potential approach for sustainable land-use policy in the newly developed arid areas and also for integrated soil and water management practices. However, further verifications through increasing soil and groundwater samples are essential to obtain better characterizations and representations for the locally dominant limitations. Moreover, future crop-based land suitability studies are recommended to validate the proposed approach under different geographic and climate conditions.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by ASA and AME-H. The first draft of the manuscript was written by ASA and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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