Section A-research paper, ISSN: 2063-5346

Assessment of soil degradation and resilience at some areas in El-Qalyubia Governorate, Egypt

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Article History: **Received**: 31.05.2023 **Revised**: 12.06.2023 **Accepted**: 21.06.2023

Abstract: Land deterioration is clearly observed in various regions with arid and semi-arid climates. Land degradation is defined as a phenomenon that leads to a decline in the ability of soil to produce goods. Soil resilience is a concept that has recently been introduced in soil science to address the ecological environment of soil and issues related to sustainable land use. The goals of this study are as follows: (1) creating a physiographic soil map of the soil in the studied area using remote sensing techniques; and (2) identifying some soil properties such as effective soil depth, bulk density, salinity, and alkalinity in the concerned area over the past 55 years in order to generate soil resilience maps and assess soil degradation. To determine the major physiographic units in the area, ENVI 5.3 software was used to process the "Landsat OlI 8" images and digital elevation model. Sedimentary deposits were conveyed among the recognized units. Morphological descriptions were conducted as well as soil samples for physical and chemical analysis. Out of thirty soil profiles, fifteen were carefully chosen to represent different map units. The locations of soil profiles were selected to be the same ones that the Soil and Water Research Institute (RISW) studied in 1967. Consequently, changes in soil characteristics have been determined over the last fifty-five years (1967-2022). The soil degradation status was assessed, and the results revealed that water logging, salinity, and alkalinity were the most active soil degradation processes. Land use and management have a direct impact on soil resilience. It has the potential to reduce soil degradation by increasing soil restoration, resulting in soil resistance.

Keywords: Soil resilience, Soil degradation, Remote sensing, GIS, Soil mapping and El-Qalyubia Governorate, Egypt

1. Introduction

Land deterioration is a complex phenomenon caused by a variety of factors, including harsh weather conditions, particularly drought, and anthropogenic activities that cause soil pollution or degradation (Abdulrahman et al., 2022 a, b, c). Furthermore, land use (Abdulrahman et al., 2022d) plays an important role in exacerbating the negative impacts on food production and livelihoods, as well as providing other ecosystem goods and services. Land degradation threatens billions of people's livelihoods, particularly vulnerable rural communities in lower and middle-income countries (Barbier and Hochard, 2016). Land degradation is defined as a phenomenon that decreases soil's current and/or potential ability to produce goods (Kawai and Droesh, 2019).

The causes of degradation differ by region, as the rate of land degradation is affected by a variety of factors such as topography, weather, and human actions. A previous study has shown that topographical factors such as slope inclination have a direct impact on the increase in degradation. Furthermore, climate factors such as rainfall and temperature influence degradation rates by controlling the spatial distribution of vegetation density, biological activities, soil erosion, salinity, alkalinity, and other factors. Human factors, on the other hand, have a significant impact on the rate of degradation, with mismanagement policies and livestock grazing having a particular impact. Furthermore, human activity plays a significant role in soil sealing, which is regarded as Egypt's main problem (Nkonya. et al., 2016). The soil resilience is defined as the soil's ability to perform its essential functions (Ludwig et al., 2018). Controlling organic matter content in the soil, improving soil structure, increasing soil diversity, reducing rates of soil degradation and erosion without affecting the natural rate of soil formation, and improving food capital and recycling mechanisms are the main processes involved in soil resilience (Biswas, 2016).

2. Material and Methods

2.1.study area

The study area is located north of Cairo; it represents part of the Nile Delta. It is located between longitudes 30° 15′ 0″ and 30° 30′ 30″ N and latitude 31° 03′ 30″ and 31° 34′ 30″ E, with an area of 1019.9 km^2. It comprises several districts, including Kafr Shukr, Banha, Qalyub, Al-Qanater Al-Khairiya, Toukh, Al-Khanka, and Shebeen Al-Qater (Fig. 1). From a geological perspective, the region falls within the late Pleistocene epoch, as indicated by prenile deposits, sand dunes, sea and water, Tertiary Alkali Olivine Basalt, Wadi deposits, and Nile silt. The geological units for this study area were extracted from CONCO (1989)'s geological map of Egypt (scale 1:500,000), as shown in (Fig.2). Based on the report by the Egyptian Meteorological Authority (2020) and the authoritative document known as the keys to soil taxonomy (USDA, 2014), the soil temperature regime in the area under study is classified as Thermic and the soil moisture regime has been identified as Aridic.

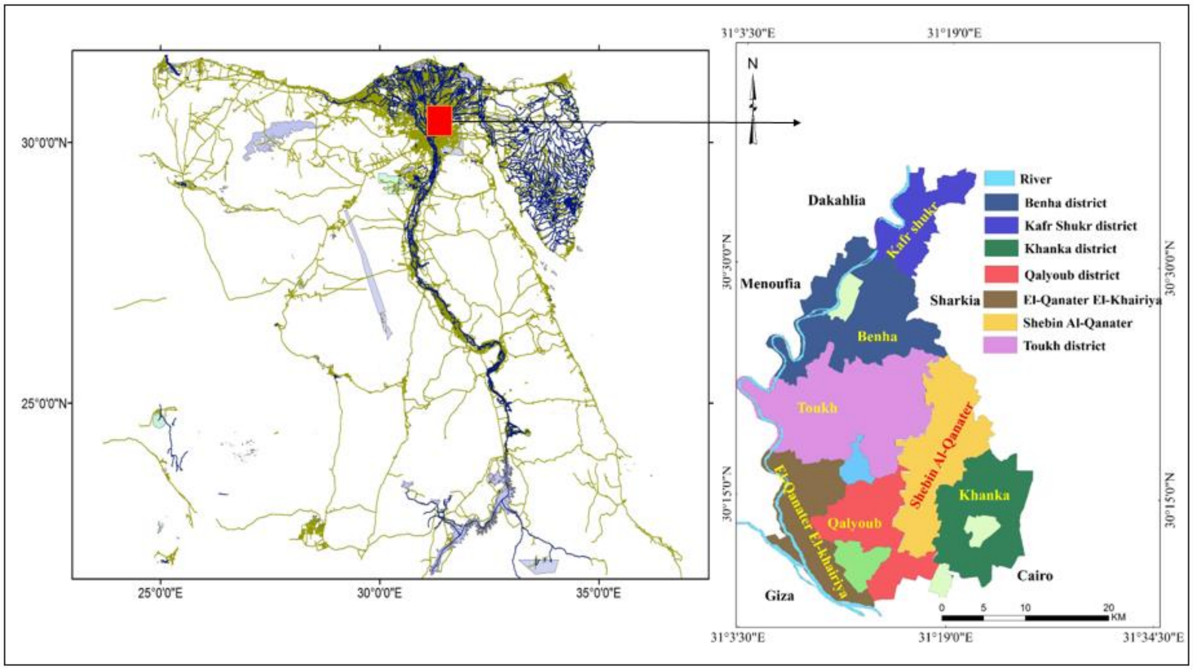

Figure 1: Location of the study area.

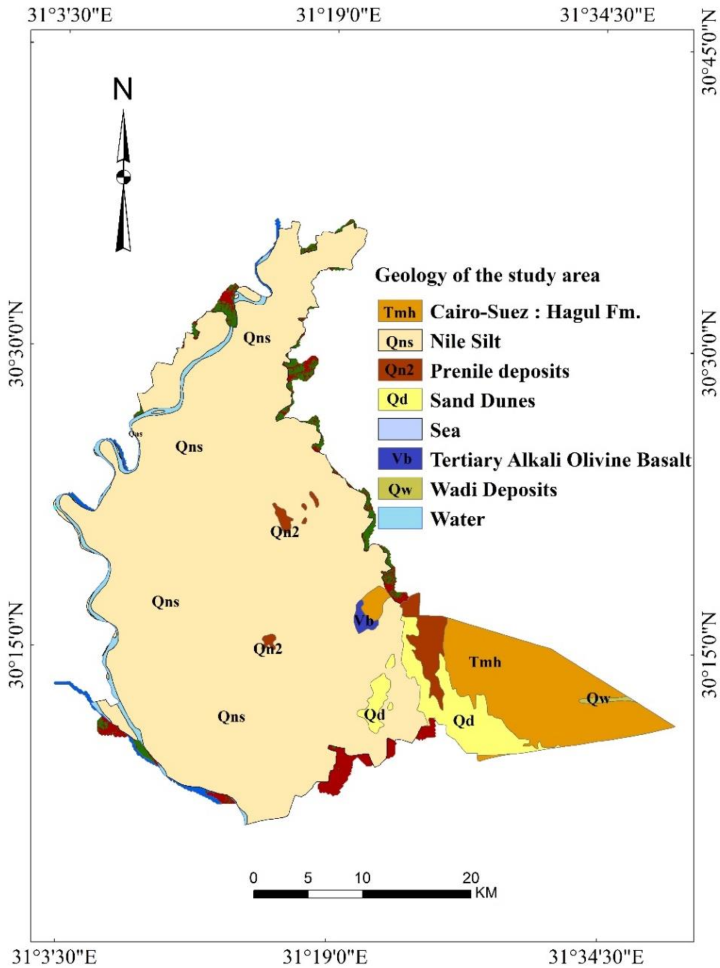

Figure 2: Geology of the study area (after CONOCO, 1989).

2.2.Landform mapping

A Landsat OLI-8 satellite image (path 176, row 39) acquired in 2021 was obtained from the Geologic Survey archive (http://earthexplorer.usgs.gov/) of the USGS. The image improvements were done by ENVI 5.3 software as depicted in Figure 3. As per the findings of Lillesand and Kiefer (2015), the most suitable combination of bands (4, 3, and 2) was utilized. Topographic map of Qalyubia Governorate, (scale 1:100000) was included in the data set. ArcGIS 10.8 software was used to manage soil databases created for the study area, as well as to map soil variables. A physiographic analysis was employed to produce a comprehensive physiographic map of the research region, then a map legend was devised in conformity with the guidelines stipulated by Zink and Valenzuala (1990).

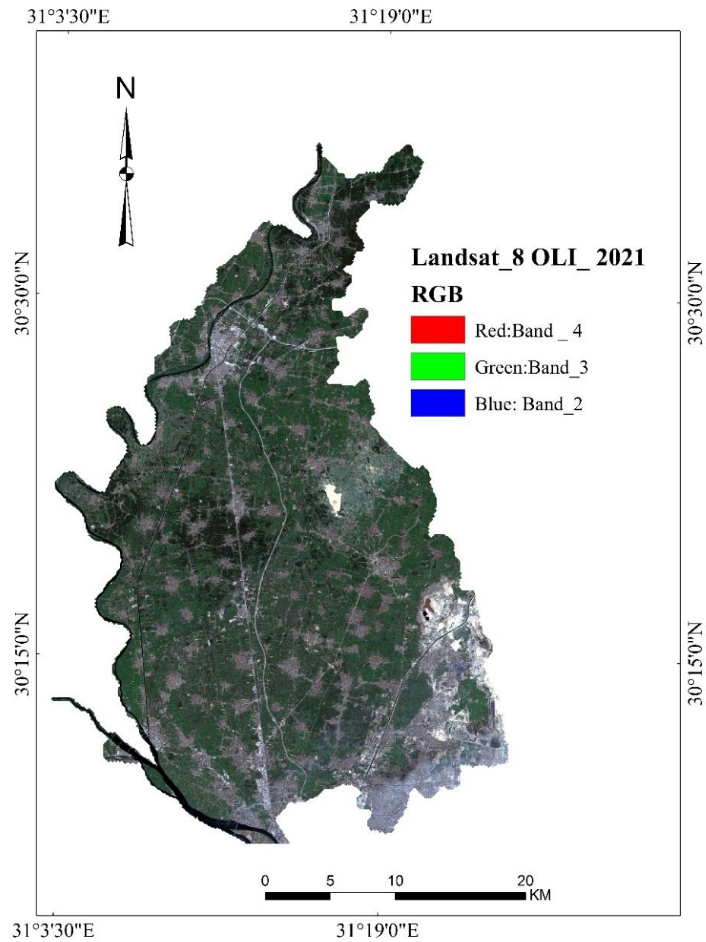

Figure 3: Enhanced Landsat OLI 8 satellite images dated to year 2021.

2.3. Fieldwork and laboratory analysis

A sum of thirty soil profiles was meticulously chosen to effectively depict the equivalent locations that had been previously investigated by the esteemed Institute of Soil and Water Research (RISW, 1967). These soil profile sites were deliberately selected in transects so as to encompass all mapping units between the years 1967 and 2022.These profiles' morphological descriptions were completed in accordance with the FAO (2006) guideline. Soil survey staff (2014) performed soil classification and taxonomy. The soil correlation between physiographic and taxonomic units was developed following the identification of the main soil sets in the studied area by Elberson and Catalan (1987). The soil samples were air-dried and gently ground before sieving through a 2 mm mesh. The soil survey laboratory techniques handbook (USDA, 2004) was used to collect and analyze representative disturbed soil samples. The conducted analyses encompassed the evaluation of the dispersion of particles, the pH of soil, the concentrations of organic matter, the proportion of CaCO3, the electrical conductivity measured in (dS/m), quantification of different cations and anions, cation exchange capacity (meq./100 g soil), and exchangeable sodium percentage.

2.4. Soil degradation assessment

The soil degradation degree reflects the extent of the degradation process, which is gauged by both the level of soil deterioration and the proportional scope of the affected region within a specified physiographic unit. The GLOSOD methodology developed by UNEP in 1991 was employed to establish and expound upon the degree, relative extent, severity level, and causative factors, which can be described as follows:

1- The rate at which soil undergoes degradation can be established by referring to Table 1, which outlines the criteria utilized for this purpose.

2- Table 2 presents the criteria that are utilized to determine the extent of soil degradation.

Table 1. Soil degradation rates.

Chemical degradation	Salinization (Cs) increase in (EC) per dS/m	Alkalinization (Ca) increase ESP/ year
Non to slight	<0.5	<0.5
Moderate	0.5 – 3	0.5 – 3
High	3 – 5	3 – 7
Very high	> 5	> 7
Physical degradation	Compaction/ increase in bulk density per g/cm^3	Water logging/ decrease in water table in cm/year
Non to slight	<0.1	<1
Moderate	0.1 – 0.2	1 – 3
High	0.2 – 0.3	3 – 5
Very high	> 0.3	> 5

Modified after FAO (1979) and UNEP (1991)

Table 2: Criteria for determining the various degradation types.

Critical/Hazard/Type	Indicator		class			
		Unit	Low	Moderate	High	Very high
Salinization	EC	dS/m	<4	4 – 8	8 – 16	>16
Alkalinization	ESP	%	<10	10 – 15	15 – 30	>30
Compaction	Bulk density	g/cm^3	<1.2	2.1 – 1.4	4.1 – 1.6	>1.6
Waterlogging	Water table	cm	>150	150 – 100	100 - 50	<50

Modified after FAO (1979) and UNEP (1991)

2.5. Soil resilience assessment

This study presents a comparative analysis between the data retrieved from RISW (1967) and the data acquired from the present investigation. Lal's (1997) method is employed to classify soil resilience into three distinct categories, namely:

2.5.1. The soil degradation processes rate

Soil resilience can be calculated by using the rate of soil quality modification, as shown in the formula below:

$$Sr = - dSq / dt$$

Where (Sq) represents soil quality (salinity, alkalinity, effective soil depth, and oxygen availability for roots) and (t) represents time, a change with a negative value indicates deterioration.

2.5.2. Soil restoration rate

The quantification of soil resilience involves evaluating the pace of soil recovery. This measurement can also be correlated with shifts in soil quality, as depicted in the equation provided:

$$Sr = + dSq/dt$$

Where Resilience is indicated by a positive value of the change.

2.5.3. *Soil resilience Modeling*

The following model was used Lal (1993b), (1994a), (1994b), (1997), (1998).

$$Sr = sa + \int_0^t (sn - sd + Im)dt$$

The present model considers various factors, including Sa denoting the initial or preceding state rate, Sn representing the soil replenishment rate, Sd indicating the rate of soil degradation, and Im signifying the management input rate. Additionally, the rate of alterations in soil characteristics, such as salinity, alkalinity, and waterlogging, were evaluated utilizing data from RISW (1967) and the current investigation. The evaluation of soil resilience involves the combination of soil quality assessment, which includes effective soil depth, salinity, and alkalinity, as outlined by Erian (1989), and the determination of soil renewal rate and management input, in accordance with Lal

(1994b), as presented in Tables 4 and 5. The classification of soils into distinct categories based on their resilience levels is illustrated in Table 6.

Table 4. Soil quality rating.

Rating	Effective soil depth (cm)	Salinity EC (dS/m)	ESP	Limitation
1	<150	>2	>10	Non
2	100 – 150	2 – 4	10 – 15	Slight
3	100 – 80	4 – 8	16 – 20	Moderate
4	80 – 50	8 – 15	21 – 30	Strong
5	>50	<15	>30	Very strong

Modified after Erian (1989)

Table 5. Soil renewal and management input rating.

Rating	**Soil renewal rate (cm/year)**	**Management input**	**Limitation**
1	>0.1	Chemical fertilizer and organic matter addition with improvement in irrigation and drainage system	Very high
2	0.06 – 0.1	Chemical fertilizer and / or organic matter addition with improvement in drainage system	High
3	0.01 – 0.05	Chemical fertilizer or organic matter addition	Moderate
4	<0.01	No management input	Low

Modified after Lal (1994a)

Table 6. Soil resilience classes (Status and Description).

Class	Resilience status	Description
0	Highly resilient	Rapid recovery, high buffering
1	Resilient	Recovery with improved management
2	Moderately resilient	Sow recovery with high input
3	Slightly resilient	Slow recovery even with change in land use
4	Non-resilient	No recovery even with change in land use

Modified after Lal (1994a)

3. Results and discussion

3.1.Physiographic and soil map

Significant features has been gathered through the examination of digital elevation models, interpretation of satellite images, and analysis of land surveying data, revealing that the designated study area consists of a primary landscape with three distinct reliefs: (a) River terraces, which include two landforms: the highest river terraces and the lowest river terraces; (b) Basin, which includes five landforms: levees (recent sand deposits and sub-recent sand deposits), overflow mantle (relatively high parts and relatively low parts), overflow basin (relatively high parts and relatively low parts), decantation basin (relatively high parts and relatively low parts), and turtle backs (isolated hills); (c) Nile deposits, with one landform: islands (recent islands and sub-recent islands). Based on (Soil Survey Staff 2014), the analyzed soils could be categorized as follows: (a) T, Typic Torrifluvents and Typic Natrargids (cons.), Vertic Torrifluvents (Assoc.); (b) L, Typic Torripsamments (cons.), OM, Typic Torrifluvents (cons.), OB, Typic Torrifluvents (cons.), DB, Typic Torrifluvents and Typic Natrargids (cons.), Typic Halosalids (Assoc.), TB, Typic Torrifluvents (cons.); (c) I and SI, Typic Torripsamments (cons.). Table 7 and Figure 4 display the primary physiographic units and soil sets in the studied region, revealing the following information:

3.1.1. Soils of river terraces

The soils encompass the highest and lowest river terraces (T1 and T2), each covering an area of (252.32 km^2). The soil depth within these terrace units varies between 15 and 100 cm, as determined by laboratory analyses conducted in 2022, and the soil texture is classified as clayey. The pH values of the soil are (7.3 and 8.1). The electrical conductivity (EC) values range from 2.81 to 4.37 dS/m, while the exchangeable sodium percentage (ESP) ranges from 7.8 to 11.8. The bulk density of the material is 1.23 g/cm^3. The $CaCO_3$ content ranges from 1.6% to 5.0%. The organic matter content ranges from 0.7 to 2.0%. The macronutrients N, P, and K have values of 37.8, 24.0, and 284 ppm, respectively.

3.1.2. Soils of the basin

Levees (L1 and L2) with (16.3 km^2) represent soils. Based on the laboratory analyses conducted in 2022, the Levees units exhibited a soil depth ranging from 20 to 80 cm, with soil reaction (pH) values ranging from 7.4 to 8.0. The electrical conductivity (EC) values within these units ranged from 3.18 to 8.32 dS/m, while the exchangeable sodium percentage (ESP) spanned from 9.0 to 10.7. The bulk density of the material is 1.14 g/cm^3. The $CaCO_3$ content ranges from 0.2% to 2.0%. The organic matter content ranges between 0.2% and 1.0%. The macronutrients N, P, and K have values of 11.7, 5.8, and 23.6 ppm, respectively. Overflow mantle (OM1 and OM2) with (115.04

km^2). Laboratory analyses carried out in 2022 revealed that the soil depth of the overflow mantle units varied from 20 to 120 cm. The pH values of the soil are (7.3 and 8.1). The electric conductivity (EC) values range from 5.31 to 8.83 dS/m. The exchangeable/sodium percentage (ESP) ranges from 9.0 to 11.7. The bulk density of the material is 1.4 g/cm^3. The $CaCO_3$ content ranges from 0.2% to 2.3%. Organic matter content ranges between 0.5 and 1.8%. The macro nutrients N, P, and K have values of 17.8, 12.7, and 78 ppm, respectively. Overflow basins (OB1 and OB2) with a total area of (247.28 km^2). The soil depth within the overflow basin units ranged from 15 to 110 cm, according to laboratory analyses conducted in 2022. The pH values of the soil are (7.3 and 8.0). The electric conductivity (EC) values range from 6.49 to 9.95 dS/m. The exchangeable/sodium percentage (ESP) ranges from 15.0 to 16.1. The bulk density of the material is 1.37 g/cm^3. The $CaCO_3$ content ranges from 0.2% to 3.3%. The organic matter content ranges between 0.2-2.2%. The macro nutrients N, P, and K have values of 42.5, 25.6, and 287 ppm, respectively. The decantation basins (DB1 and DB2) covers 327.51 km^2, the soil depth of these units ranged between 20 and 100 cm, according to laboratory analyses conducted in 2022. The pH of the soil is (8.1 and 8.3). The electric conductivity (EC) values range from 5.14 to 14.4 dS/m. The exchangeable/sodium percentage (ESP) ranges from 15.4 to 21.3. The bulk density of the material is 1.72 g/cm^3. $CaCO_3$ content varies between 0.3% and 1.0%. The range of organic matter content falls between 0.4% and 1.5%. The macronutrients N, P, and K have values of 38.3, 18.9, and 299 ppm, respectively. Regarding to the turtle backs (TB) with (1.101 km^2), the laboratory analyses indicated that the soil depth of the turtle-back units varied from 20 to 140 cm. The pH of the soil is (7.3 and 7.8). The electric conductivity (EC) values range from 3.9 to 5.1 dS/m. The exchangeable/sodium percentage (ESP) ranges from 14.5 to 15.1. The bulk density of the material is 1.17 g/cm^3. The $CaCO_3$ content ranges from 0.2% to 5.0%. The organic matter content ranges from 0.2-0.8%. The macronutrients N, P, and K have values of 10.8, 20.0, and 210 ppm, respectively.

3.2.3. Soils of islands

Soils are represented by islands (I1 and SI1) with (17.74 km^2). The islands had soil depths ranging from 15 to 80 cm, according to laboratory analyses conducted in 2022. The pH of the soil is (7.2 and 7.9). The electric conductivity (EC) values range from 2.62 to 5.72 dS/m. The exchangeable/sodium percentage (ESP) ranges from 8.4 to 9.8. The bulk density of the material is

1.14 g/cm^3. $CaCO_3$ content varies between 0.1% and 0.5%. Organic matter content ranges between 0.1% and 0.6%. N, P, and K are the macronutrients represented by 14.9, 6.1, and 21.2 ppm, respectively.

Table 7. Soil and physiographic map key

Landscape	Relief	Lithology/origin	Land form	Mapping unit	Area Km^2	Profile No	Soil Taxonpmy	Type of soil sets
Alluvial plain	River Terraces	Sequence of river terraces	The Highest river terraces	T1	189.02	8	Typic Torrifluvents	Cons.
						28	Vertic Torrifluvents	Assoc.
			The lowest river terraces	T2	63.3	30	Typic Natrargids	Cons.
	Basin	Levees	Recent sand deposits	L1	11.02	15	Typic Torripsamments	Cons.
			Sub-recent sand deposits	L2	5.28	19	Typic Torripsamments	Cons.
		Overflow mantle	Relatively high parts	OM1	54.91	5	Typic Torrifluvents	Cons.
			Relatively low parts	OM2	60.13	9	Typic Torrifluvents	Cons.
		Overflow basin	Relatively high parts	OB1	124.57	11	Typic Torrifluvents	Cons.
			Relatively low parts	OB2	122.71	6	Typic Torrifluvents	Cons.
		Decantation basin	Relatively high parts	DB1	101.01	23	Typic Torrifluvents	Cons.
			Relatively low parts	DB2	226.5	20	Typic Natrargids	Cons.
						10	Typic Haplosalids	Assoc.
		Turtle backs	Isolated hills (complex)	TB	11.01	26	Typic Torripsamments	Cons.
	Nile deposits	Islands	Recent islands	I1	4.53	18	Typic Torripsamments	Cons.
			Sub-recent islands	SI1	13.21	13	Typic Torripsamments	Cons.

Cons. Consociation, assoc. association

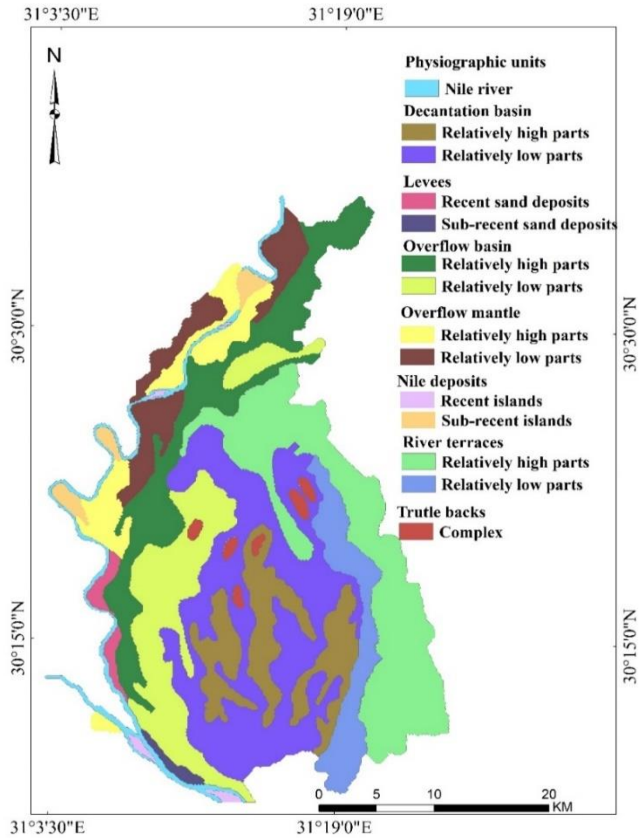

Figure 5: The physiographic units of the studied region, modified after Kawy and Darwish., (2019).

3.2.Soil degradation

Investigations on soil degradation indicators across different soil types were conducted with the goal of evaluating waterlogging, compaction, salinization, and alkalinization processes in the designated regions. The calculation of land degradation rate involved a comparison between essential soil attributes recorded in 1967 and those assessed in 2022 (Table 8). According to the data collected, annual increases in EC, ESP, and bulk density contribute to a drop in the water table level. Except for instances of waterlogging in I1, SI1, and L2 soils, soil degradation occurs gradually. Between 1967 and 2022, the water table dropped from 100 to 60, 100 to 80, and 100 to 80 cm in these cases. Land degradation ranges in severity from minimal to extremely significant, with measurements of electrical conductivity, exchangeable sodium percentage, bulk density, and water table depth falling within the respective intervals of 2.62 to 14.4 dS/m, 7.8 to 21.3%, 1.10 to 1.40 g/cm³, and 60 to 150 cm. The soils of Decantation basins DB1 and DB2 will be affected by very high salinization (EC >8 dS/m) in 2022, accounting for % of the total area. From 1967 to 2022, the soils of Decantation basins DB1 and DB2 and Overflow basins OB1 and OB2 experienced a high degree of alkalinization (ESP 15 - 30), accounting for 56.33% of the total area. between 1967 and 2022, a significant portion of the study area, comprising Decantation basins DB1 and DB2, Overflow basins OB1 and OB2, and Overflow mantles OM1 and OM2, exhibited moderate soil compaction (bulk density 1.2 - 1.4 g/cm/), covering approximately 67.63% of the total area. In contrast, recent islands (I1), sub-recent islands (SI1), and Levees (sub-recent deposits L2) all experienced substantial waterlogging (soil depth 60 - 100 cm). The evaluation of the extent of each soil degradation type within the surveyed region was achieved through geomorphology-soil correlation (Fig 7,8,9, and 10).

Table 8: Water table, bulk density, EC, and ESP changes between 1976 and 2022.

Profile No.	Mapping unit	Water table level (cm)		Bulk density (g/cm^3)		EC(dS/m)		ESP	
		1967	2022	1967	2022	1967	2022	1967	2022
17	I1	100	60	1.1	1.11	2.62	4.82	8.7	9.8
26	SI1	100	80	1.13	1.14	3.0	5.72	8.4	9.6
18	L1	110	80	1.12	1.13	3.18	5.1	9.2	10.8
16	L2	100	80	1.14	1.14	4.0	8.32	9.1	10.7
25	OM1	120	110	1.3	1.4	5.31	8.61	9.0	9.9
27	OM2	130	120	1.27	1.3	6.0	8.83	10.6	11.7
28	OB1	120	110	1.29	1.37	6.49	9.17	15.0	15.8
24	OB2	120	110	1.26	1.31	7.24	9.95	15.9	16.1
15	DB1	110	110	1.24	1.53	5.14	10.6	15.8	21.4
5	DB2	120	90	1.3	1.69	6.25	12.4	15.4	20.6
11	DB2	130	100	1.4	1.72	7.5	14.4	16.7	21.3
8	TB	150	140	1.16	1.17	3.9	5.1	14.5	15.1
2	T1	120	110	1.18	1.23	2.81	3.68	9.4	11.8
4	T1	120	100	1.2	1.3	2.92	3.82	9.8	12.2
13	T2	110	100	1.15	1.17	3.19	4.37	7.8	10.2

Bulk density, EC and ESP were Calculated for the upper 100 cm of the soil profile

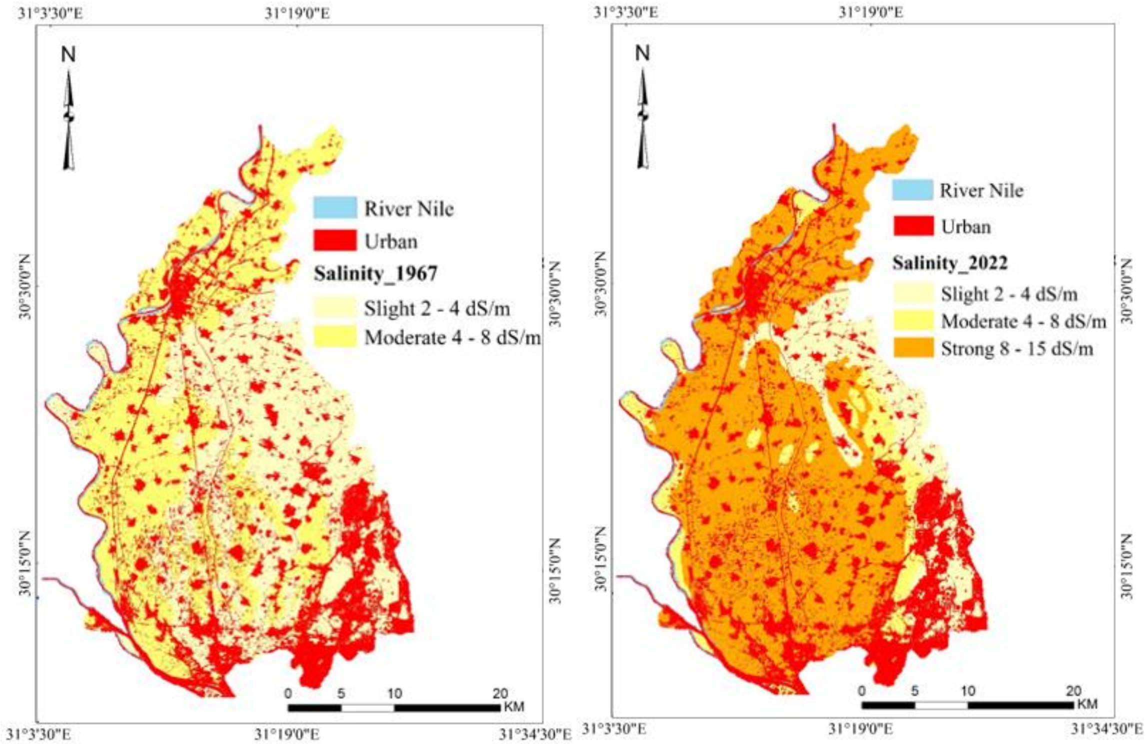

Figure 7. Salinity change detection between 1967 – 2022 according to Erian (1989)

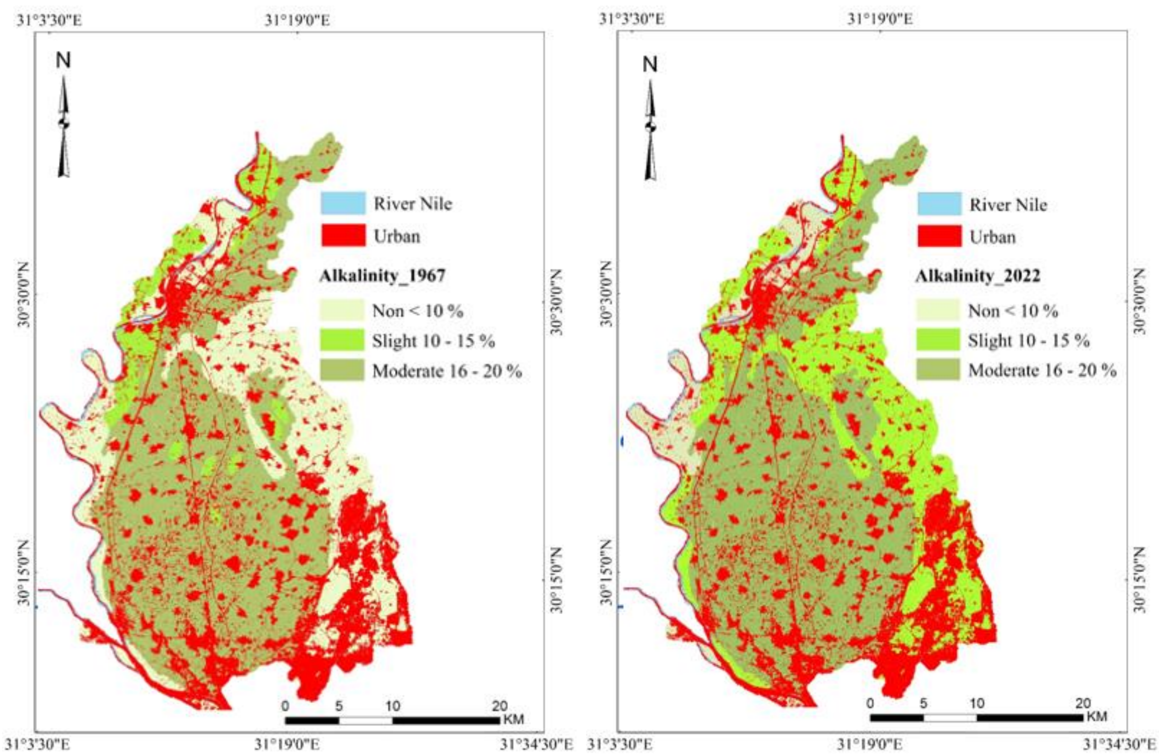

Figure 8. Alkalinity change detection between 1967 – 2022 according to Erian (1989)

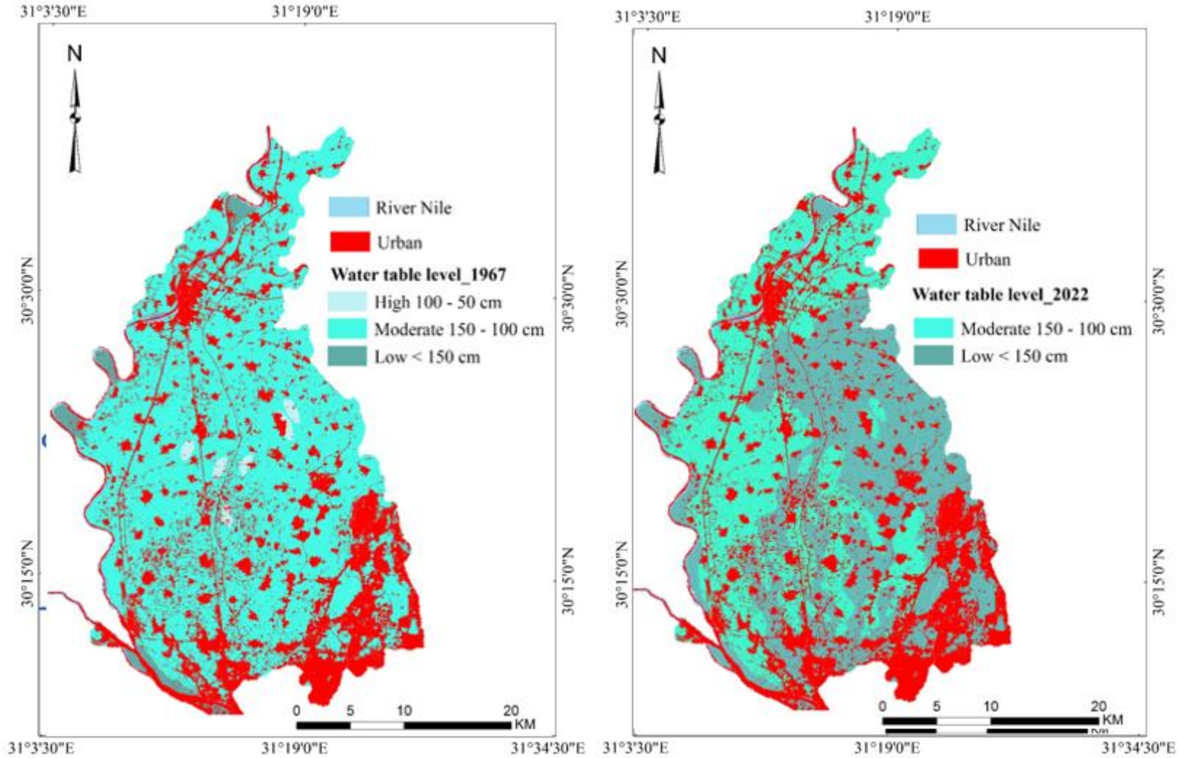

Figure 9. Water table level change detection between 1967 – 2022 according to FAO (1979) and UNEP (1991)

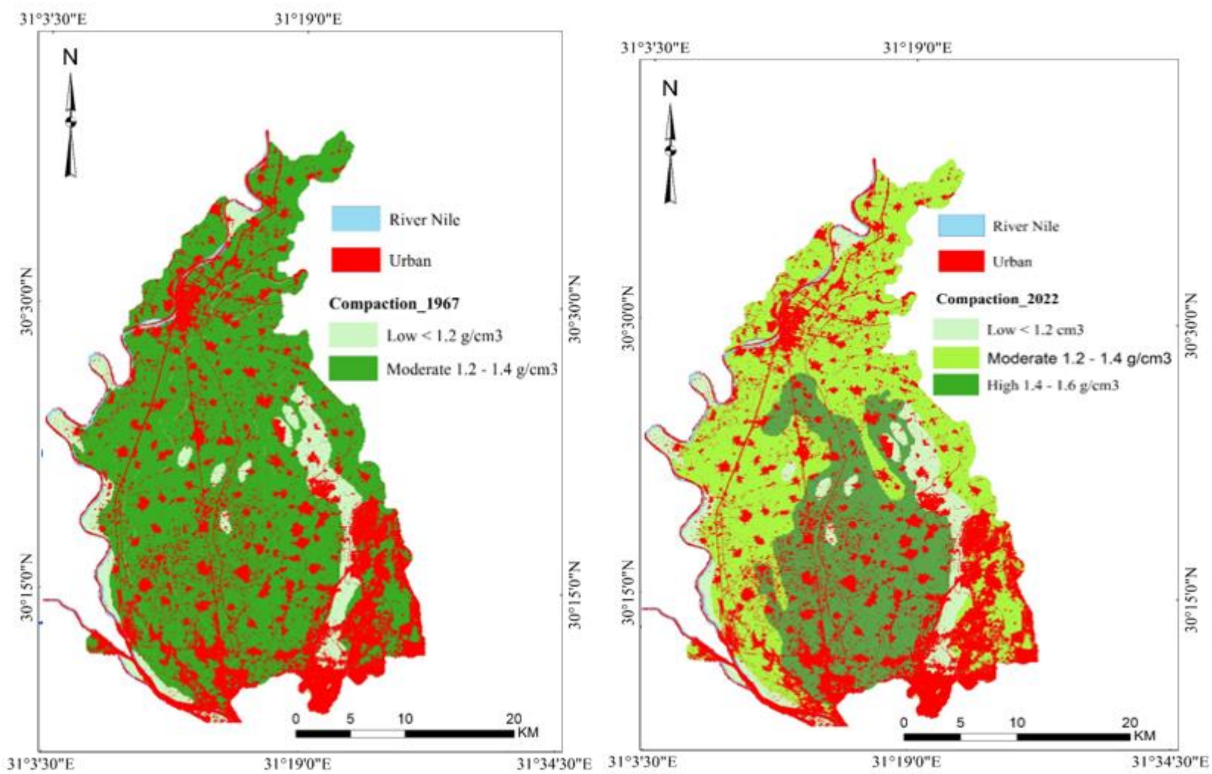

Figure 10. Compaction change detection between 1967 – 2022 according to FAO (1979) and UNEP (1991)

3.3.Soil resilience

The Soil resilience in the study area was assessed using soil degradation rates (Sr.deg), soil restoration rates (Sr.rest.), and modeling (Sr.mod.).

3.3.1. Soil resilience according to the rate of soil degradation

The soil resilience analysis based on the degradation rate of the primary soil units within the study area is depicted in Table 9 and Figure 11. Soil resilience is moderate in recent islands (I) and decantation basins (DB), which cover 332.11 km2 and account for 33.6% of the total area. Sub-recent Islands (SI), Levee (L), overflow mantle (OM), overflow basin (OB), Turtle backs (TB), and river terraces (T) soils, which cover 655.19 km^2 and account for 66.36% of the total area, have either no or minor soil resilience.

3.3.2. Soil resilience according to the rate of soil restoration

Table 10 and Figure 12 present soil resilience based on the rate of soil restoration. River terraces (T) soils, covering 252.36 km^2 (25.56% of the total area), exhibit high resilience, characterized by swift recovery and strong buffering capacity. On the other hand, soils in recent islands (I), sub-recent Islands (SI), levees (L), overflow mantle (OM), overflow basin (OB), and turtle backs (TB) with an area of 407.37 km^2 (41.26% of the total area) show moderate resilience and gradual recovery under optimal management practices. However, the soils of the decantation basin (DB), spanning 327.57 km^2 (33.17% of the total area), exhibit no resilience, despite changes in land use, rendering them non-resilient.

3.3.3. Soil resilience according to modeling

The study area is divided into three resilience categories based on the modeled soil resilience shown in Table 11 and Fig 13: none to slight, moderate, and high. T, TB, OM, OB, L, and SI cover 641.99 km^2 (approximately 62.98%) and have non-to-slight soil resilience. Recent islands (I) cover 4.54 km^2 (approximately 0.45% of the total area) and exhibit moderate soil resilience. The decantation basin (DB), on the other hand, covers 327.57 km^2 (approximately 33.17%) and has high soil resilience.

1.1.1. Determined classes of soil resilience

The assessment of soil resilience involved the establishment of connections among the three previously cited resilience indices (Sr. deg, Sr. rest., and Sr.mod.), as outlined in Table 12 and Figure 14. According to the findings, soils demonstrating high resilience (Class 0) within the research zone display intermediate levels of permeability for soil degradation (Sr. deg), slight to negligible levels for soil restoration (Sr. rest.), and notable levels for modeling (Sr.mod.). These soils are predominantly found in the decantation basin (DB), covering 407.37 km^2 (41.26% of the total area). The water table in this unit ranges from 90 to 120 cm deep, with an electrical conductivity between 5.14 and 14.4 dS/m and an exchangeable sodium percentage between 15.4 and 21.4. Chemical fertilizers, manure incorporation, and drainage system improvement are all common land management strategies in these areas.

On the other hand, soils categorized as non-to-slight resilient (class 2) in the research area exhibit permeability levels ranging from non-to-slight (Sr.deg) for soil degradation, to moderate (Sr.rest.) for soil restoration, and non-to-slight (Sr. mod.) for modeling. These soil types predominantly occupy sub-recent Islands (SI), Levee (L), Overflow mantle (OM), Overflow basin (OB), Turtle backs (TB), and river terraces (T), covering an extent of 655.19 km^2 (constituting 66.36% of the entire area). The water table depth within these unit's spans from 60 to 130 cm, while electrical conductivity varies between 2.81 and 9.95 dS/m, and the exchangeable sodium percentage ranges from 7.8 to 16.1. Conventional land management practices, such as the application of chemical fertilizers, the addition of manure, and the implementation of enhanced irrigation and drainage systems, are routinely adopted for these soil types.

Finally, Resilient soils (classified as class 1) within the research zone exhibit slopes of moderate incline for soil degradation (Sr.deg), moderate levels for soil restoration (Sr.rest.), and moderate permeability for modeling (Sr. mod.). These soil types predominantly exist in recent islands (I), encompassing an area of 4.54 km^2 (comprising 0.45% of the total land area). The water table depth in these units is relatively shallow, ranging from 60 to 100 cm, and their electrical conductivity falls within the range of 2.62 to 4.82 dS/m, while the exchangeable sodium percentage varies between 8.7 and 9.8. Conventional management practices such as the application of chemical fertilizers, incorporation of manure, and the implementation of enhanced drainage systems are frequently employed to maintain these soil types.

Table 9: Soil resilient according to the rate of soil degradation

Mapping unit	dSw/dt	dSz/dt	dSa/dt	dSc/dt	limiting factor	-dSq/dt	Sr.deg.	Area Km^2
I	-1	0	0	0	W	-1	Mod	4.54
SI	0	0	0	0	W	0	non to slightly	13.21
L	0	0	0	0	W	0	non to slightly	16.29
OM	0	0	0	0	z	0	non to slightly	115.04
OB	0	0	0	0	z,a	0	non to slightly	247.27
DB	0	-1	-1	-1	z,a,c	-1	Mod	327.57
TB	0	0	0	0	-	0	non to slightly	11.01
T	0	0	0	0	-	0	non to slightly	252.36

High=0, mod=1, non to slight=2. Sq is soil quality (d is the effective depth, z is salinity, a is alkalinity), t is time and sr.reg. is the soil resilient according to the rate of soil degradation. The negative value of the change refers to degradation

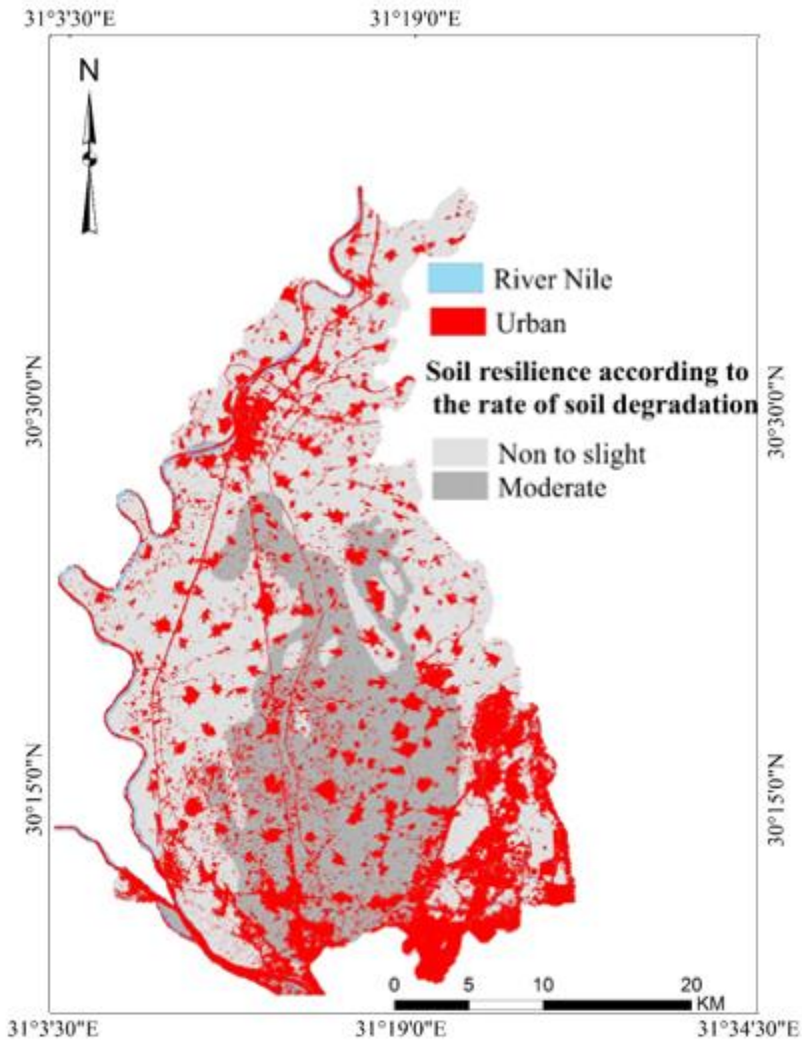

Figure 11: soil resilience based on the soil degradation rate within the studied area.

Table 10: Soil resilient according to the rate of soil restoration

Mapping unit	dSw/dt	dSz/dt	dSa/dt	dSc/dt	limiting factor	-dSq/dt	Sr.deg.	Area Km^2
I	1	1	1	1	1	1	Mod	4.54
SI	1	1	1	1	1	1	Mod	13.21
L	1	0	0	0	1	1	Mod	16.29
OM	1	1	1	1	1	1	Mod	115.04
OB	1	1	1	1	1	1	Mod	247.27
DB	0	0	0	0	0	0	non to slight	327.57
TB	1	1	1	1	1	1	mod	11.01
T	2	2	2	2	2	2	High	252.36

High=2, mod=1, non to slight=0. Sq is soil quality (d is the effective depth, z is salinity, a is alkalinity), t is time and sr.rest. is the soil resilient according to the rate of soil restoration. The positive value of the change refers to resilience

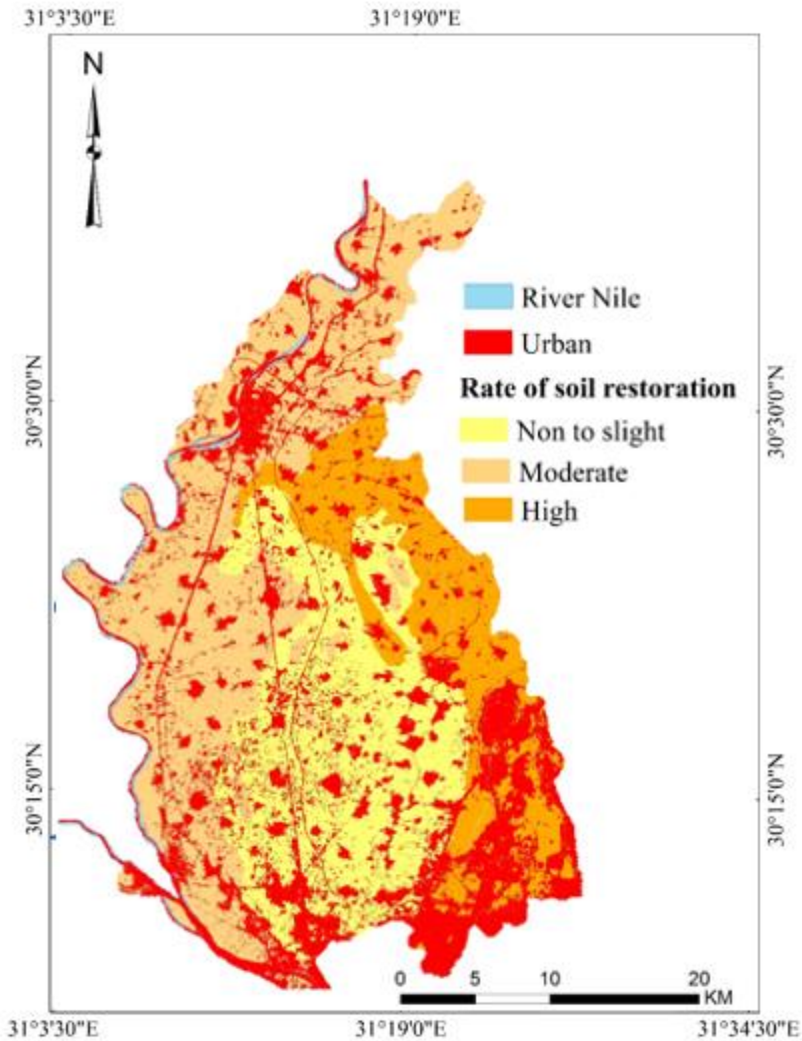

Figure 12: Soil restoration rate in the studied area.

Table 11: Soil resilience as indicated by modeling

Mapping unit	sa	sn	sd	Im	sr.mod.	Area Km2
I	2	2	2	3	mod	4.54
SI	2	2	2	3	non to slightly	13.21
L	2	2	2	3	non to slightly	16.29
OM	2	2	2	3	non to slightly	115.04
OB	2	2	2	3	non to slightly	247.27
DB	1	1	3	2	High	327.57
TB	2	1	1	4	non to slightly	11.01
T	1	1	1	4	non to slightly	252.36

Sa is the rate of the initial condition, Sn is the rate of soil renewal, Sd is the rate of soil degradation, Im is the management input rates and sr.mod. is the soil resilient according to modeling.

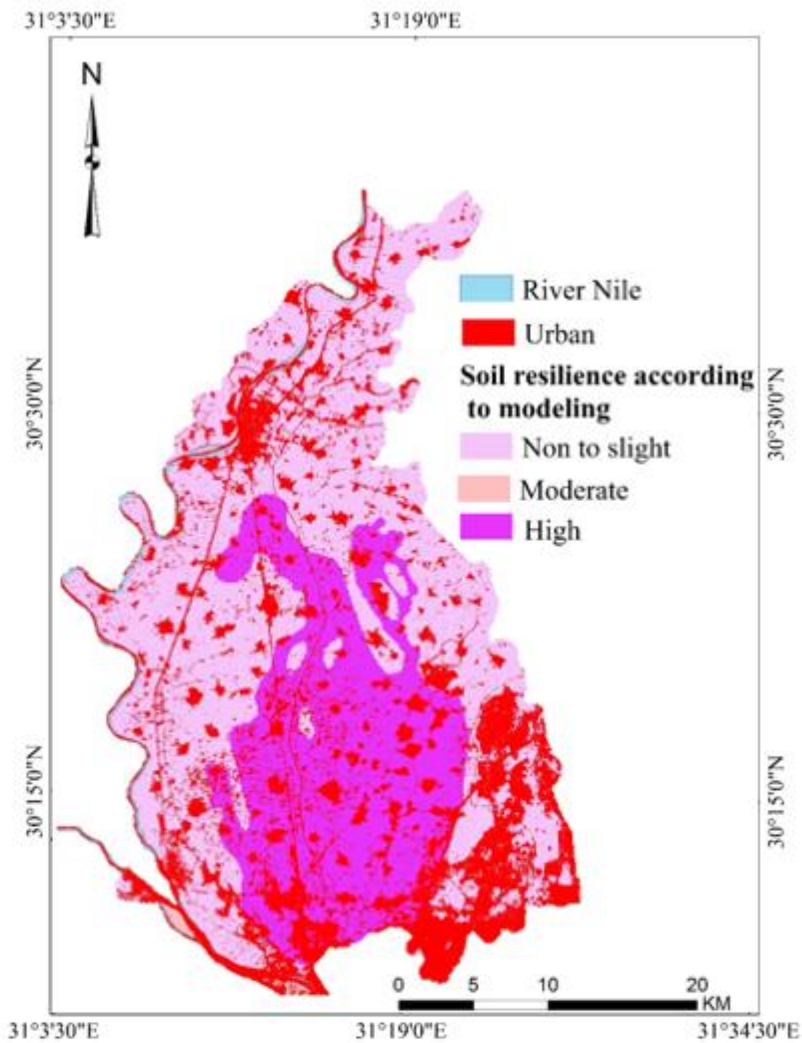

Figure 13: Soil resilience over the study area

Table 12: Soil resilience classes

Mapping unit	sr (degradation)	sr(rest)	sr(model)	sr (class)	sr concluded)	Area Km2
I	mod	mod	mod	1	Resilient	4.54
SI	non to slight	mod	non to slight	2	mod resilient	13.21
L	non to slight	mod	non to slight	2	mod resilient	16.29
OM	non to slight	mod	non to slight	2	mod resilient	115.04
OB	non to slight	mod	non to slight	2	mod resilient	247.27
DB	mod	non to slight	High	0	High resilient	327.57
TB	non to slight	mod	non to slight	2	mod resilient	11.01
T	non to slight	High	non to slight	2	mod resilient	252.36

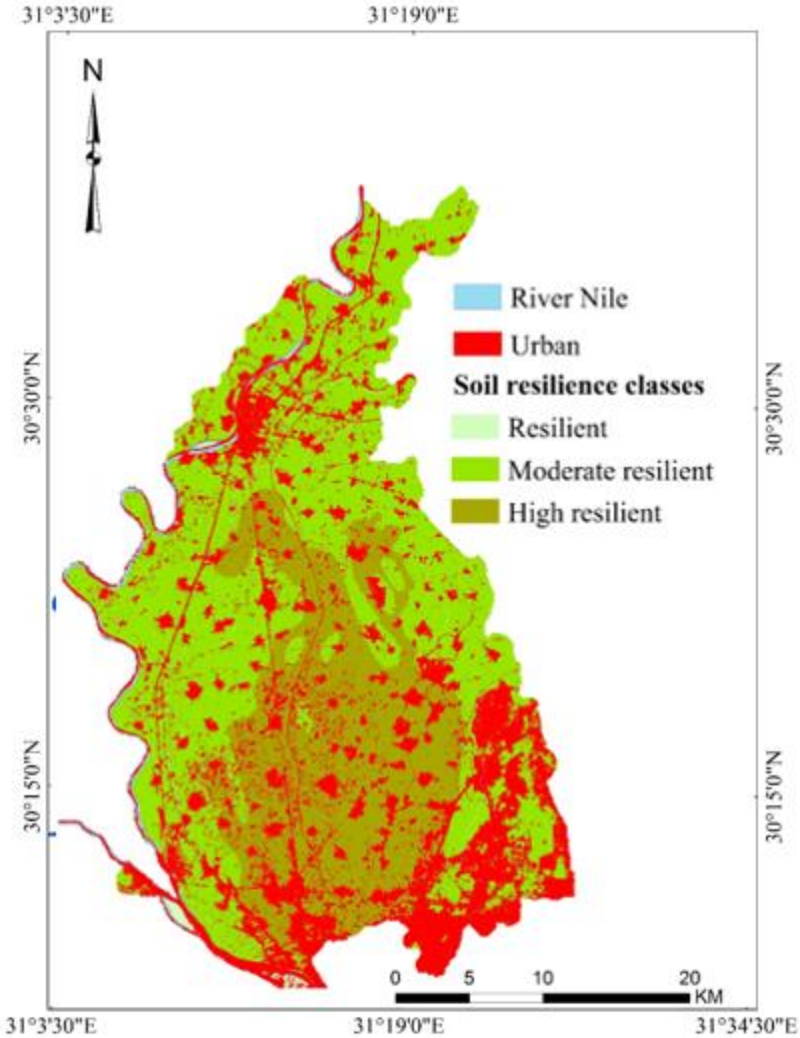

Figure 14: Soil resilience classes

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4. *Conclusion*

Land use and management directly influence soil resilience; this could have a significant impact on mitigating soil degradation and promoting soil restoration, consequently enhancing overall soil resilience. Human negative activities in the study area encompass three main types (e.g. over irrigation, improper machinery timing). Assessing soil resilience in relation to human activities depends on the implementation of suitable land management practices, including modern irrigation and drainage techniques, as well as appropriate fertilization protocols.

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