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SUSTAINABLE MANAGEMENT OF SOIL RESOURCES IN WADI WARDAN, SUEZ GULF REGION, SOUTHWESTERN SINAI, EGYPT

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ABSTRACT: Egypt's land resources deteriorate due to soil mismanagement under the limited natural resources while the population increases. This issue highlights the importance of efficient soil resource management to increase crop yield and meet growing food needs. This study offers sustainable soil resource management for each soil type in Wadi Wardan, Suez Gulf region, South Sinai, Egypt, maximizing land usage and crop output while avoiding soil degradation. Wadi Wardan, spanning 300 km^2, is believed to hold promising soil resources in South Sinai. From upslope to downslope, five landforms were mapped in Wadi Wardan: the recharge area of Wadi tributaries (33 km^2; unsampled), pediment (105 km^2), fluvial plain (54 km^2), Wardan's delta (87 km^2), and coastal plain (21 km^2). Eighty-nine pedons were proportionally dispersed over only four landforms in Wadi Wardan. Soils range from shallow to deep, with well-drained to poorly-drained conditions. The studied soils were coarse-to-fine in texture. Soils range from nonsaline on upslopes to very strongly saline on downslopes. The studied soils range from slightly to extremely calcareous. High ρb values and low organic carbon levels indicated soil problems in Wadi Wardan. Six mapping units were established depending on soil depth, texture, salt, and lime content. Based on WRB soil taxonomy, most soils in the pediment and fluvial plains are classed as Leptosols (69.3 km^2), Regosols (42.5 km^2), and Calcisols (39.7 km^2), while those in Wardan's delta are Sololnetz (43 km^2) and Solonchaks (51.5 km^2). Coastal plain soils are classified as Arenosols (21 km^2). Based on WRB, Solonchaks has a horizon sequence of A-Btz-C/Bt-Cz containing salic horizon and soil limitations related to high salinity content (9.1-21.1 dS/m). Natric and salic horizons in Sololnetz's Ap-E-Btnz-C sequence indicate sodium and salt restrictions. The Arenosol layer sequence (A-Ck-Cq-Cz-Cφ) suggests deep sandy-saline soil, while the Leptosol layer sequence (C-Cφ) shows shallow sandy soil with over 30% rock fragments. Each soil type requires unique management depending on dominating features that limit plant development. The current study proposed a sustainable soil management framework for each soil type identified in the study. Incoherence, nutrient storage, and erosion sensitivity plague Arenosols. Salts affect three types of soils under study to varying degrees: saline sandy soils (Arenosols) with a coarse texture that end at a depth of 172 cm, and salts are concentrated in the lower layers (Cz layer at a depth of 106-153 cm) of the pedon, reaching more than 27 dS/m. The strongly saline soils, particularly in the upper 50 cm of the pedon, have a moderately fine textured soil, particularly in the salic horizon (Btz) in Solonchaks, which finishes at 149 cm deep. The third kind is represented by Sololnetz with a fine texture, and it is the most harmful because it combines high salinity and high alkalinity in the fine texture of the soil, as in the Btnz horizon at a depth of 57-100 cm. Each of these soil types has a unique management strategy to try to remove salts from the rooting zone by increasing water and gypsum requirements, like Sololnetz. In addition to calcareous soils, which have a calcic horizon, as in Calcisols, and require sustainable management to deal with the lime content and calcic horizon, there are also soils affected by high lime content that do not fall under Calcisols because they lack a calcic horizon, such as Leptosols and Regosols, and each of them requires completely different management from the others. Address reduced soil potentiality in Calcisols by strategically placing fertilizers, adding organic matter for stable aggregates, and deep ripping to penetrate the compacted calcic horizon and allow roots to reach water and nutrients. Increasing organic matter and limiting compaction can lower bulk density and porosity in all soils under study. Balanced fertilization and saline agriculture are key Solonchak control measures. Solonetz improvement involves enhancing soil porosity and decreasing ESP. Future ideas may outline a paradigm for sustainable agriculture management, focusing on completeness, diversity, sophistication, and longevity.

Key words: Solonchaks, Sololnetz, Leptosols, Soil management, Adoption spectrum.

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INTRODUCTION

Egypt aims to expand its agricultural sector to address food security, population growth, and land infringement and boost exports and national income. The Sustainable Development Strategy (SDS): Egypt Vision 2030 addresses development concerns in Egypt (MCIT, 2020). Challenges include limited natural resources (e.g., energy, land, and water), environmental deterioration, and inadequate human development resources (e.g., population, health, education). Egypt relies on the Nile and Nasser Lake, which are discharged through the Aswan High Dam (Omran and Negm, 2020). Egypt's population lives on less than 5% of the country's 1,000,000 km^2 of land. No periodic census of agricultural areas, urban encroachments, and cultivated lands makes accurate estimation difficult using traditional surveying methods (Omran and Negm, 2020). Over the past decade, the Sinai Peninsula has gained importance for discovering new agricultural lands to accommodate population growth. Soil and water resources are the focus of numerous research initiatives across the peninsula. This study examines soil and groundwater resources in the Delta of Wadi Wardan on the Sinai West coast, focusing on soil cover thickness and water table depth. The electrical resistivity method was utilized due to its efficacy in locating geologic or hydrologic boundaries in similar locations (Omran and Negm, 2020).

Soils are crucial to ecosystems and require multidisciplinary approaches to comprehend their dynamics. The lithosphere, biosphere, atmosphere, and hydrosphere interaction generates soil. It controls most landscape ecosystem processes, houses significant biodiversity, and is the physical underpinning for human activity. Since the first agricultural revolution, human impacts on soil have worsened (Brevik *et al.*, 2015). Soils play a role in ecological regulation and human civilization. Our existence relies on them as they provide vegetation, raw materials, and food production. Sustainable management of soil resources is essential to maintain the amount and quality of the environment offered by this conditionally renewable resource (Han and Niles, 2023).

Several governments worldwide prioritize sustainable soil management through land management instruments or soil-specific regulations. Some countries may include soil management restrictions in their agriculture, land, environment, and water laws (FAO and UNEP, 2020). Additional soil-specific rules may handle water-related issues. Soil science approaches are evolving due to their expanding scientific and practical significance. Recent remote/proximal sensing advances have improved soil mapping and characterization (Sorokin *et al.,* 2021). However, soil classes should aid sustainable management. Soil names and classes describe various features. Classification systems are often chosen based on legislative actions, customs, scientific trends, or geopolitical factors rather than thoroughly evaluating existing systems. The World Reference Base (WRB) is an international soil categorization system based on the FAO-UNESCO Legend of the Soil Map of the World. The objective is to detect natural and manufactured soils within the first two meters of earth's surface. All modern soil classification schemes use diagnostic criteria. The WRB consists of two hierarchical levels: 32 RSGs at the first level and an undefined number at the second. To identify soils, combine the RSG with qualifiers (IUSS Working Group WRB, 2022).

Research on soil and water conservation measures for sustainable soil management has been conducted worldwide (Briak *et al.*, 2019; Berihun *et al.*, 2020; Ricci *et al.*, 2020; Afroz *et al.*, 2021; Gashaw *et al.*, 2021). Understanding the impact of soil conservation methods is crucial for effective land use management. Conservation strategies include soil management, vegetation, and structural measures (Gashaw *et al.*, 2021). These methods reduce soil erosion and salinization. Soil management strategies like enhancing soil structure, covering the soil surface with vegetation, and changing landscape topography can increase soil infiltration rate and minimize rain impact. Uniyal *et al.* (2020) assessed the impact of vegetative and structural practices in an Indian watershed. The study found that structural best management practices reduced sediment yields and surface runoff more effectively than vegetative ones. Berihun *et al.* (2020) found that using only vegetative measures on-farm trials in Southern Germany reduced soil loss by 98% compared to intensive tillage. Afroz *et al*. (2021) used the SWAT model to simulate soil management scenarios in an Indian watershed, including conservation, zero, and field agriculture. The results showed a 9% drop in sediment output compared to traditional tillage (Zhen *et al.,* 2023).

Due to restricted resources, Egypt explored natural and non-conventional water sources, including groundwater. In Egypt, groundwater is the second primary water supply after the Nile River, with 7.2 billion cubic meters pumped annually (NWRP, 2017). Arid to hyper-arid climates cover 97% of the country, with barely 4% in the Nile delta (GEF, 2009). New desert projects have been launched primarily utilizing groundwater for land reclamation. The goal is to decrease population pressure in the Nile Valley and delta and create new farming communities to meet the country's expanding food security needs. The 1.5 million Faddans mega-project, begun in December 2015, involves reclaiming agricultural land in the Western Desert and drilling over 1,500 wells in the fossil aquifer (Isin and Konandreas, 2017). Exploration of these projects is constrained by global constraints such as climate change, groundwater extraction, and declining land and water quality. Climate change and rising global temperatures reduce groundwater discharge, lowering piezometric levels in nearby aquifers (Gona *et al.,* 2022).

However, the Egyptian deserts are degraded due to land and groundwater salinization, water scarcity, and wind erosion (Negm and Elkhouly, 2021; Said *et al.,* 2022). Further research is needed to assess the possibilities for sustainable management and development of natural resources such as land and water. Before this study, soil resources in Wadi Wardan, South Sinai, were not thoroughly explored. To effectively manage soil resources in Wadi Wardan, soil morphology, physical, and chemistry studies are necessary to evaluate soil types. This research examines the features and assessment of soils according to their vertical distribution over the soil pedon. Land allocation, tenure, and rights have been a major concern in agricultural expansion through settlement programs in new areas. Settlement plans and their impact on agricultural development are commonly studied at a macroeconomic level due to interventionist agriculture policy. The Gulf of Suez coastline zone experiences seasonal flash floods despite freshwater constraints. Wadi Wardan, northeast Gulf of Suez, Sinai, Egypt, has developed moderately due to urbanization and tourism in recent years. These advancements are expected to grow in the future. Thus, soil engineering qualities are crucial for city expansion. This study aims to improve and propose a framework for soil resource management and exploitation in Wadi Wardan for sustainable soil management for each type of soil.

MATERIALS AND METHODS

Study Area

The research region, which has a total surface area of almost 300 km^2, is located in northwest south Sinai and is bordered by latitudes 32°41′ E and 33°09′ E and longitudes 29°22′ N to 29°39′ N (Fig. 1). The study area was bounded to the east by the El-Tih plateau and to the west by the Gulf of Suez. Floods that threaten the villages and people who live along the main streams may transport large amounts of silt. The Delta of Wadi Wardan is located about 50 kilometers south of Suez, on the eastern shore of the Gulf of Suez (Fig. 1). It is directly south of Ras Sudr. Mobile sands predominate on the Plio-Pleistocene and, more recently, unconsolidated sediments that cover the shoreline plain in the Wadi Wardan area (Said, 1962).

In the southern region of Sinai, wadis are formed as a deeply carved network of valleys in the mountainous area and as a network of sediment deposits in the flat area in front of the mountains. The research area is a strategic and viable target for agricultural and urban growth. Nonetheless, natural disasters frequently target it, most notably the high-velocity flash floods that occurred on January 17-18, 2010. Roads, bridges, tourist attractions, water and oil pipelines, Bedouin settlements, and urban infrastructure suffer more damage with each runoff. Wadi Wardan is one of Sinai's busiest wadis, with previous floods severely damaging homes and destroying large sections of road. Many different types of sediment from surface runoff episodes in the Wadi Wadi Wardan basin have frequently ruined the Suez-Sharm El-Sheikh highway.

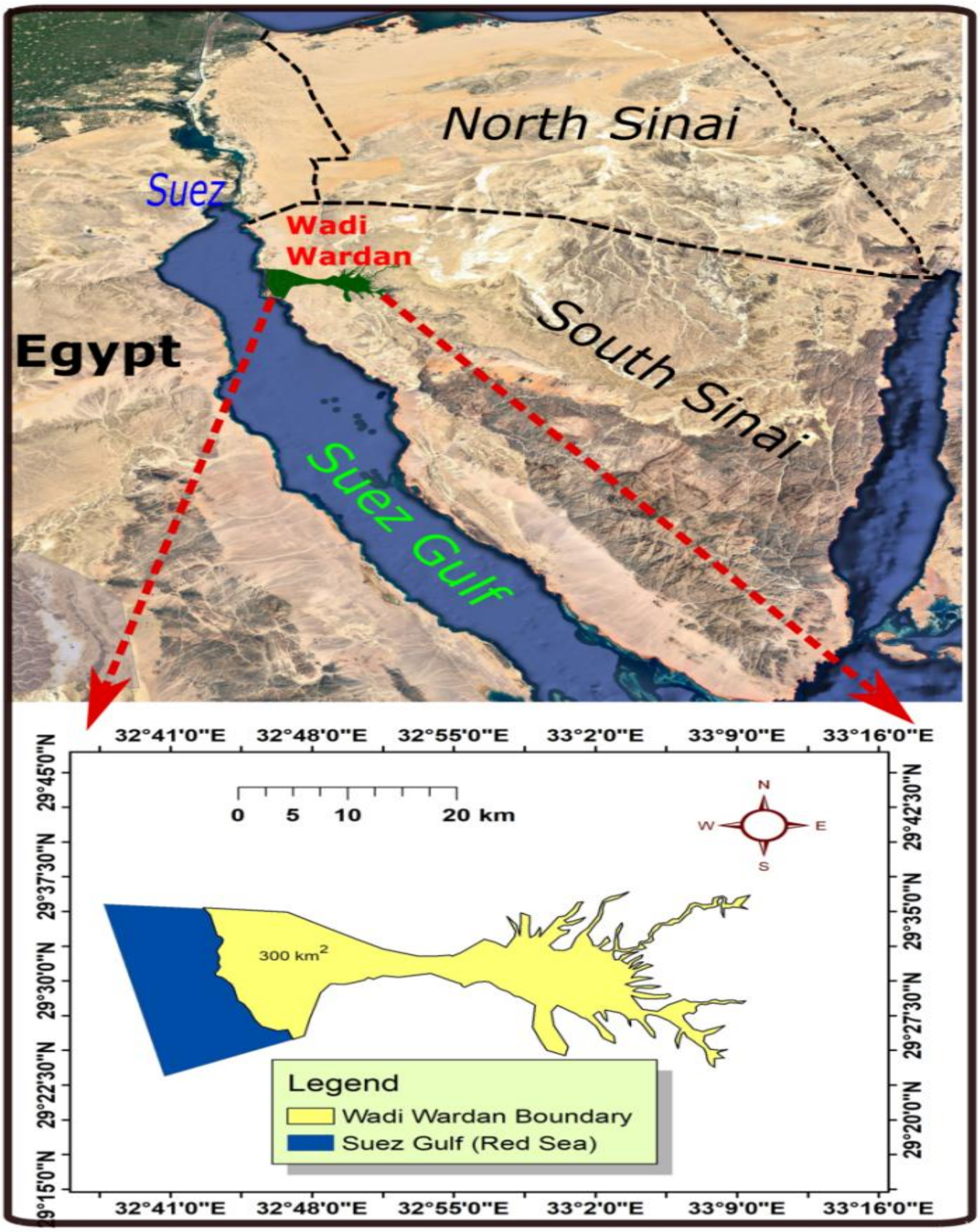

Fig. (1): Location of Wadi Wardan study area.

Geomorphologic Setting

The Wadi Wardan basins' geomorphology can be categorized into the following units (Figs. 2 and 8): The structural plateau is the western boundary of the El-Tih plateau. The elevation ranges from 893m in Gebel Somar, 916m in Gebel Dahak, 859m in Gebel Umm Hemth, 751m in Gebel Um Holwa, 670m in Gebel Debtha, and 822m in Gebel Um Hemth. Bare Upper Cretaceous Limestone forms its surface (Fig. 4). The plateau's steep slope is on the escarpment's upper part. In contrast, the gentle slope is the lower portion of the escarpment, the limestone's weathering product. The Wadi Wardan Delta's electrical resistivity investigation has shown a pattern of variation in the region's soil cover thickness and water table depth (Fig. 3). Given the thickness of the soil zone, the fresh bearing formation, and the groundwater quality, the southern portion of the region has been shown to have greater agricultural potential (Sayed and Abdul Latif, 1985). It can guide future planning for water wells or land use construction. It was discovered that the water table in Wadi Wardan was located between 6.5 and 10.5 meters below the surface.

In comparison, the soil's thickness ranged from 0.5 to 2.2 meters (Fig. 3). The usual NE-SW fault that controls the area's structure affects both the soil and the bearing formation, causing both to thicken in the southern portion of the region. Knowing the soil thickness and depth to the water table map shown in Fig. 3 can greatly aid water well drilling and land use planning (Sayed and Abdul Latif, 1985). However, due to its higher soil and water potential, the southern portion of the region should receive more attention. Unconsolidated deposits, lagoon deposits, and salt crusts make up the elevated plateau. This part of the plateau is cut up by numerous valleys that extend westward. The dunes ran parallel to the Gulf shoreline and were made up of loose calcareous deposits.

Geologic Setting

The geology of the studied area has been researched by a number of authors, including Said (1962), Hammad (1980), Garamoon (1987), Hasanein (1989), and Gad (1996). The sequence of stratigraphy represents the Upper Cretaceous to Quaternary sedimentary strata that dominate in the research area. The primary lithostratigraphic units that dominate the research region can be arranged in the order shown in Fig. 5 from oldest to youngest. The Upper Cretaceous rocks, which are Centomonian in age and have a Matallah Formation, are made up of sandy shales with intercalations of limestone and phosphatic marl. Their thickness varies greatly between 65 and 165 meters. The Lower Senonian Duwwi Formation is composed of clastic chert beds that alternate in strata. The Sudr Formation, which is Maastrichtian in age, covers the Wadi El-Meliha subbasin. There is a thickness of 247 m. Dolomitic limestone and white chalk make up its composition. Tertiary rocks are found in the Gharandal Group, Ras Malab Evaporite Group, Extrusive Basaltic Rocks, Esna Formation, Egma Formation, and Al-Hajj Formation. The Esna Formation (Paleocene age) is composed of dark green shale with a grayish-yellow marly limestone ring in the center. It is layered on top of the Thebes and Sudr formations. The Lower Eocene Egma Formation is composed of chalky limestone with flint bands, nodules at the base, and thin, consecutive chert bands on top. Olivine basalt is an extrusive basaltic rock type.

The Al-Hajj Formation is a sandy matrix with a conglomerate of limestone cobbles and pebbles. Pleistocene and Holocene sediments (Quaternary deposits) cover the primary channels of the Wadi under study. Wadi, sabkha, and alluvial sediments make up the majority of these deposits (Fig. 5). The history of faulting and sedimentation has resulted in multiple structural layers. The lowest structural level is made up of pre-Miocene rocks that were faulted prior to and during early rifting. Miocene rocks span older, less faulted layers in the middle structural level. The topmost structural level interacts with younger late Miocene rocks. These structures overlap older structures and are separated by a few faults.

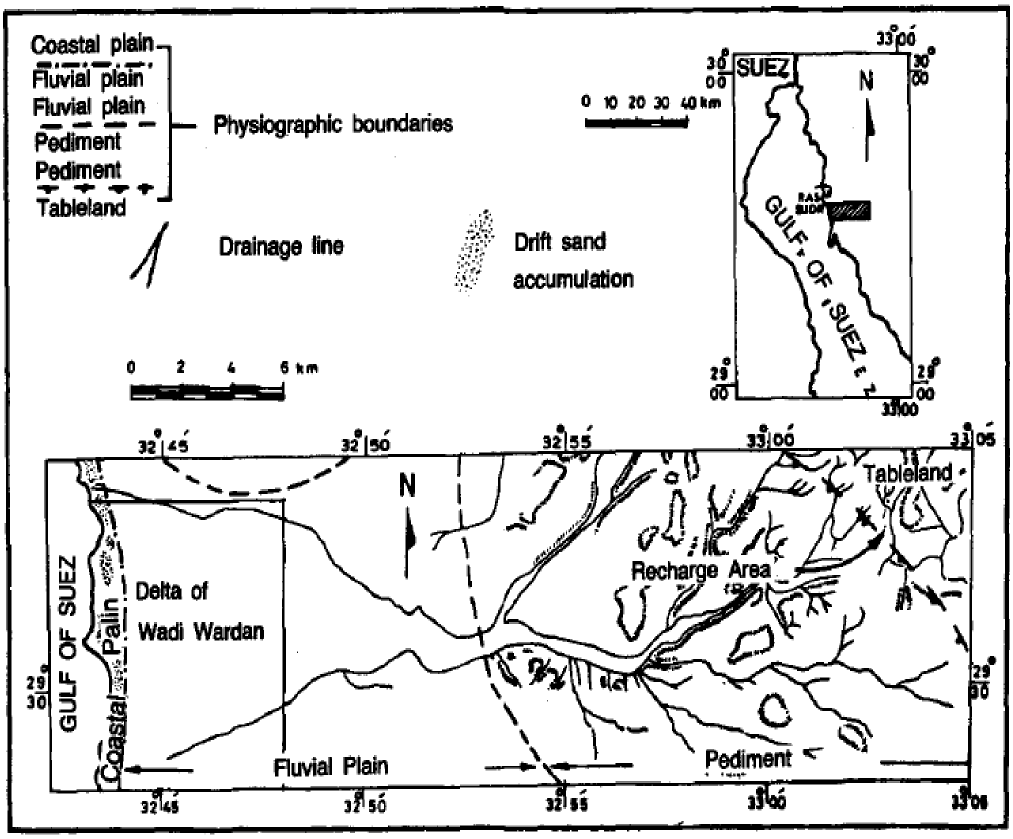

Fig. (2): Physiography of the area (Sayed and Abdul Latif, 1985).

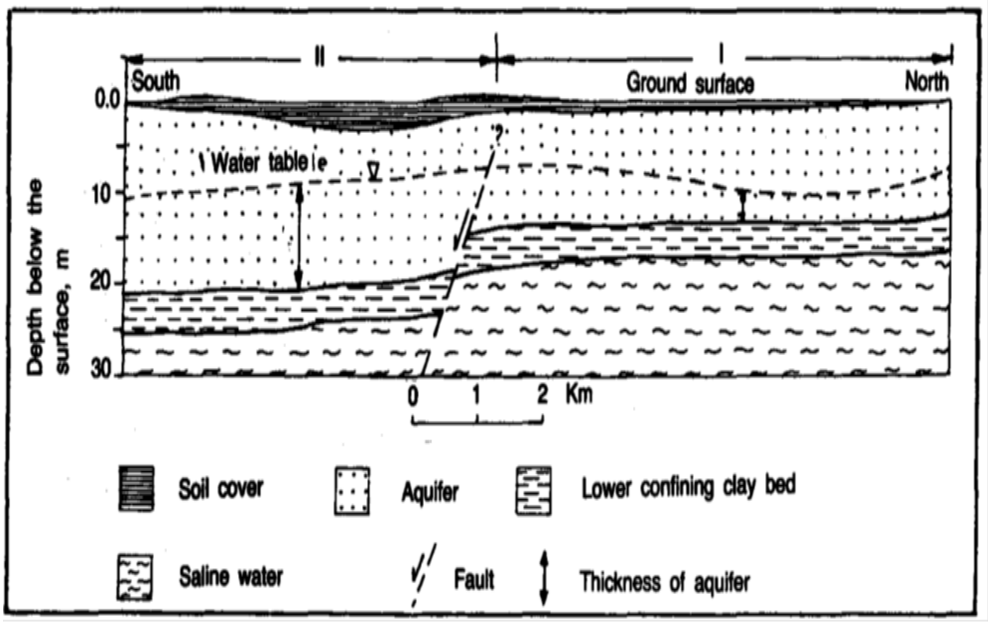

Fig. (3): A diagrammatic cross-section through the soils of South Sinai's Wadi Wardan (Sayed and Abdul Latif, 1985).

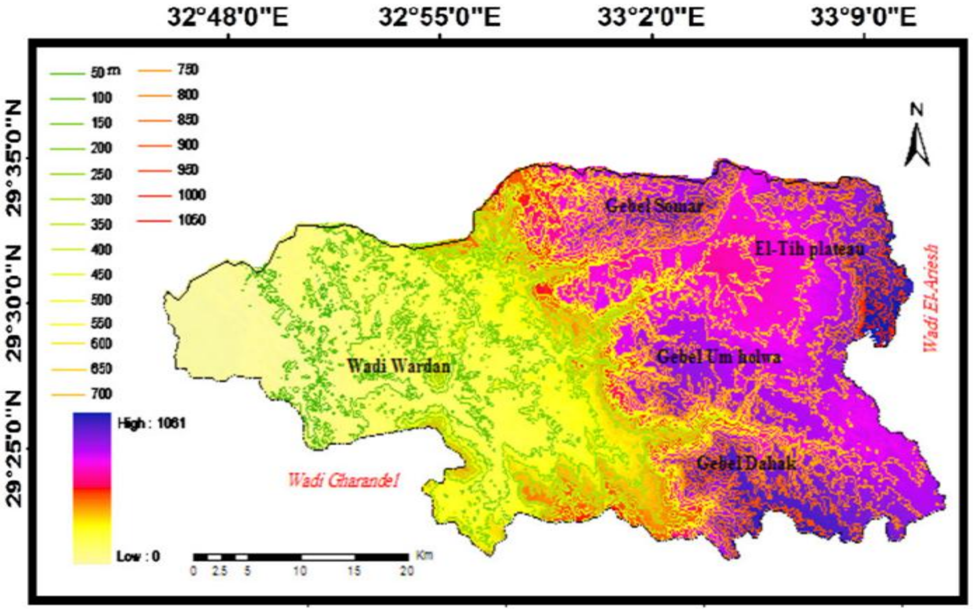

Fig.(4): Contour lines and DEM of Wadi Wardan basin.

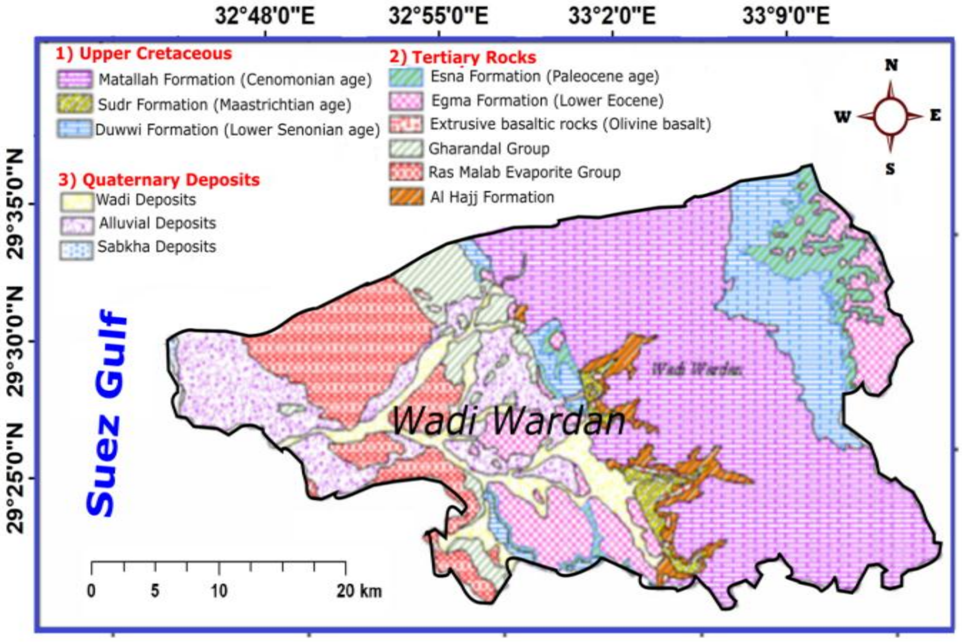

Fig. (5): Geological map of the Wadi Wardan basin.

Climatic Conditions

There are similarities between the climate of the Sinai Peninsula and other desert regions across the globe. They include a lengthy, scorching summer without rain, a mild winter, and high aridity. In the winter, wadi beds overflow in some parts of Sinai due to intense but brief rainfall, sometimes resulting in severe flash floods that damage roads and occasionally claim lives (Abdel-Lattif and Sherief, 2012). The Sinai Peninsula's climate is comparable to other desert regions worldwide. They include a lengthy, scorching summer without rain, a mild winter, and high aridity (Fig. 6). In the winter, wadi beds overflow in some parts of Sinai due to intense but brief rainfall, which can sometimes result in severe flash floods that damage roads and occasionally claim lives (Abdel-Lattif and

Sherief, 2012) (Fig. 6). The severity of flash floods has significantly increased due to human activities and the expansion of human settlements. This condition has led to the loss of human lives and animals, infrastructure damage, and socioeconomic issues (Abdel-Lattif and Sherief, 2012).

In the research area, there is a transitional phase (November–December) between the long summer (April–October) and the short winter (January–March). While the daily mean temperature has been recorded at approximately 37.2°C at Sharm El-Sheikh, 35.5°C at Ras Sudr, 35.4°C at Nekhel, and 32.9°C in Abu Rudeis, July is thought to have the greatest temperature of the year. With a mean temperature of 0.5°C at St. Catherine, 0.7°C at Nekhel, 8.4°C at Ras Sudr, and 9.9°C at El-Tur, January has the lowest temperatures, while December has the lowest mean temperature at Nekhel, 0.9°C, and 1.8°C at St. Catherine. It is significant since evaporation in the research area is far higher than precipitation. Variables including temperature, relative humidity, wind speed, plant cover, and solar radiation affect evaporation values (Fig. 6).

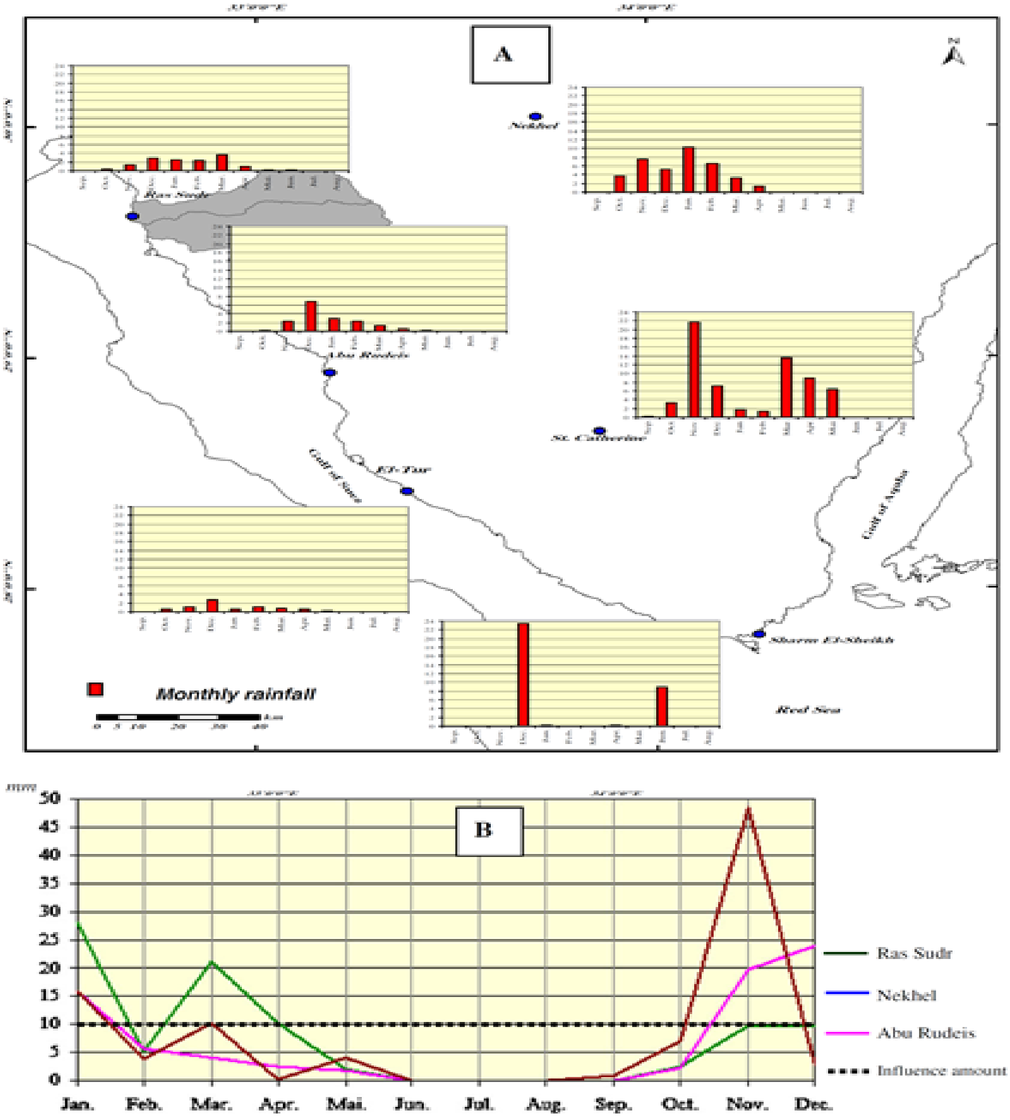

Fig. (6): The rainfall conditions across different climate stations. A) monthly average rainfall across different climate stations; B) highest rainfall value in one day.

The highest amount of rainfall recorded in one day is considered an important variable to study rainfall distribution and runoff, especially in arid and semi-arid zones. The values that record >10 mm of rainfall in one day often lead to runoff and flash floods. Thus, it could be based on these values in the study area to estimate the capability of runoff events. (Fig. 6) expressed the highest amounts of rainfall ever being recorded in one day and their dates; it can be noticed that St. Catherine station had the highest amount of rainfall in one day, reaching 37.1 mm (spring season). This station had six runoff events during the recording period (25 years), whereas rainfall was more than 10.0 mm/day. This range of rainfall is sufficient to produce runoff. The autumn months have the highest probability of rainfall at this station (Fig. 6a). Ras Sudr Station also had some high amounts of rainfall in one day (>10.0 mm/day). The effectiveness of these rainfall amounts is less than those in the Catherine area because of the occurrence of sedimentary rocks and deposits with high infiltration rates. The summit area of Sinai around Catherine consists of primary rocks (Fig. 6b).

The Wadi Wardan is found to be affected by the flash flood hazard because of some touristic villages and other infrastructure in the delta of the basin (Abdel-Lattif and Sherief, 2012) (Fig. 7).

Field Work

In Wadi Wardan, 89 pedons were spread proportionally throughout four landforms: 7 for the coastal plain, 29 for Wardan's delta, 18 for the fluvial plain, and 35 for the pediment (Table 1; Fig. 8). Georeferenced pedon points were gathered using GPS, and GIS was utilized to examine the sampling points on maps. Morphological variables were assessed for each pedon, including horizon depth, soil texture, slope gradient, erosion degree, root-restricting depth, drainage, and surface fragmentation (Schoeneberger *et al.*, 2012; Soil Science Division Staff, 2017). The soil color was evaluated by comparing samples to a Munsell Soil Color Chart (Munsell Color, USA).

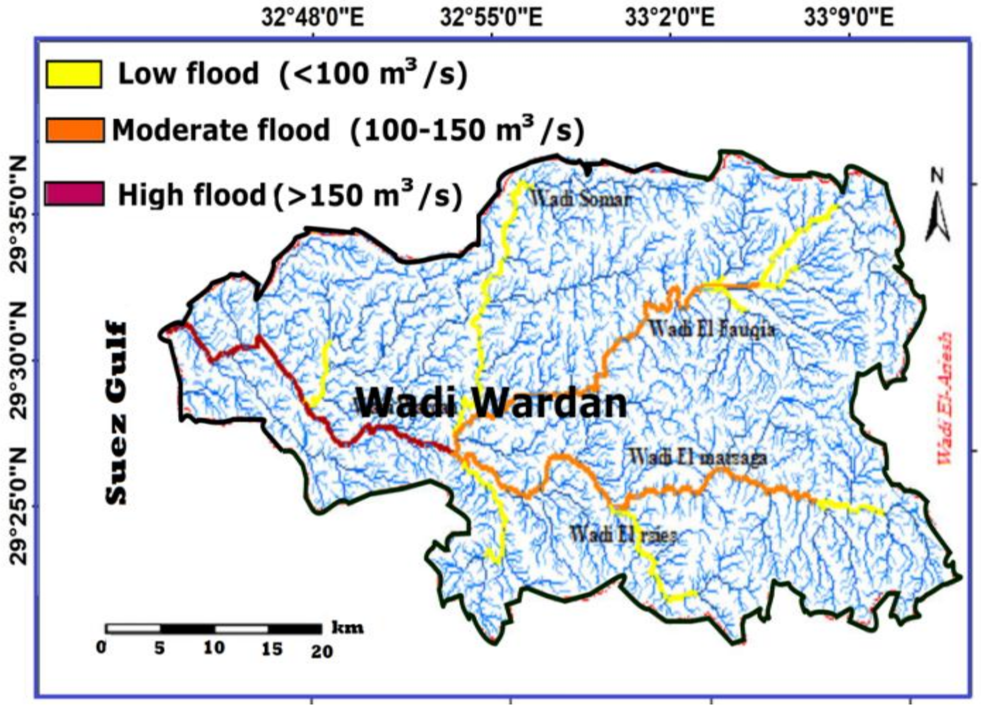

Fig. (7): Flood hazard distribution in Wadi Wardan study area.

Table (1): The landforms of the Wadi Wardan research region.

Landform	Slope position	Areal coverage		Sampled pedons
		(km^2)	(%)	
Coastal plain	Toeslope	21 km^2	7%	7 pedons
Wardan's delta		87 km^2	29%	29 pedons
Fluvial plain	Backslope to footslope	54 km^2	18%	18 pedons
Pediment	Shoulder to backslope	105 km^2	35%	35 pedons
Recharge area (Tributaries)	Summit	33 km^2	11%	Not sampled
Total	--	300 km^2	100%	89 pedons

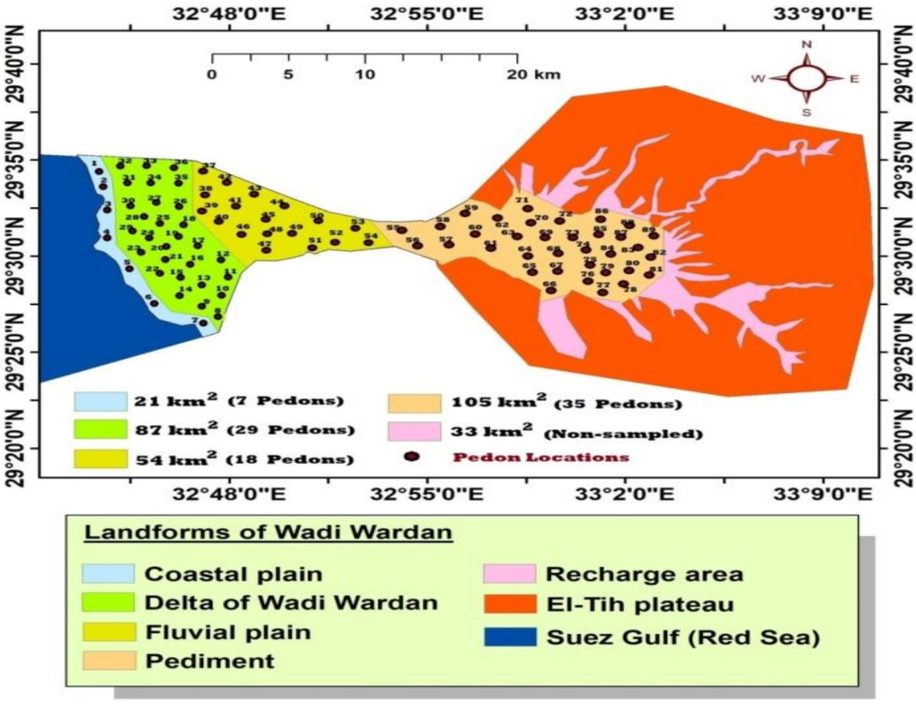

Fig. (8): Pedon locations distributed on the identified landforms of Wadi Wardan.

Soil Physical and Chemical Laboratory Analyses

Soil samples from all pedon layers were air-dried, crushed, and sieved through a 2-mm sieve to remove fine earth from coarser bones. Soil Survey Staff (2004) used the equation: rock fragments content (%) = (weight of coarse materials/weight of coarse and fine materials) × 100 to define coarse fraction (>2 mm in diameter). The pipette method was used to measure soil texture (Pansu and Gautheyrou, 2006). For each horizon, soil bulk density (ρb) was determined using the intact core method (Grossman and Reinsch, 2002). Measurements of soil electrical conductivity (EC_e), pH, lime, gypsum, exchangeable sodium percentage (ESP), and organic carbon (C_{org}) followed Burt and Soil Survey Staff (2014) protocols.

An hour was spent shaking 2 g of each soil sample with 50 mL 0.5 M KOH to extract the ASi form. After filtering, the sample supernatant was collected in a 100 mL polypropylene measuring flask. Add 50 mL 6.0 M HCl to the soil sample from the previous stage and shake for one hour. After filtering the combination, the supernatant was collected in polypropylene measuring flasks (McKeyes *et al.*, 1974). All ASi extractions were filtered using 0.45 µ Millipore sheets to remove dark tints from dissolved organic components. The extractions' ASi was colorimetrically measured using molybdenum blue (Hallmark *et al.*, 1982).

According to Jehangir *et al.* (2013), soil salinity was categorized for soil mapping units based on Table (2); other soil properties were grouped according to the FAO (2006).

Data Analysis

ArcGIS 10.1 (ESRI, Redlands, CA) was used for geostatistical studies of soil characteristics. Categorical maps were created from the acquired maps. The category maps defined soil homogenous units and categorization maps. Only pedons with dominating traits for each landscape and cultivation age were reported for morphological data. In each soil mapping unit, physical and chemical data were interpolated.

RESULTS AND DISCUSSION

Pedon Descriptions and Soil Types

The study examined soils in four landforms: the coastal plain, Wadi Wardan delta, fluvial plain, and pediment (Tables 1 and 3). Soil Typification categorizes soils based on a comparable set of dominant properties into classes or units that may be georeferenced and mapped. Based on the prior soil attributes, the soils of Wadi Wardan were classified into soil types and are shown in Table (3). Meanwhile, these soils have been classified into six reference soil groups (RSGs) according to IUSS Working Group WRB (2022). These are Arenosols, Solonchaks, Solonetz, Calcisols, Regosols, and Leptosols, which range from lowland to highland (Table 3; Fig. 9). Arenosols are deep sandy, strongly saline, slightly calcareous soils having a salic horizon at depths more than 100 cm, found solely on the coastal plain (21km^2) (Table 3). Solonchaks are deep, loamy, and extremely saline, with a salic horizon within 50 cm of the surface, covering 51.5 km^2 and extending across a considerable amount of Wardan's delta (Tables 3 and 4). Solonetz is clayey, strongly saline, somewhat calcareous soil with natric and salic layers in the top 100 cm of the soil profile that covers an area of 43 km^2. Calcisols are 39.7 km^2 in size and are moderately loamy, nonsaline, and strongly calcareous, with a calcic horizon (Bkc; Table 5) within 97 cm. Regosols, which cover 42.5 km^2, are moderately deep sandy, moderately saline, strongly calcareous soils with densic bedrock at 75 cm (Cα layer). Leptosols are shallow, sandy, nonsaline, strongly calcareous soils that cover an area of 69.3 km^2 and have lithic bedrock at 41 cm of Cα layer (Tables 3 and 4).

Vertical root-restricting layers were identified at various depths within the soil profile (refer to Table 4). At depths exceeding 100 cm, soil pedons representing Arenosols contained excessive salts and a salic horizon; pedons of Solonchaks contained a salic horizon within 50 cm of the surface; pedons of Solonetz contained natric and salic horizons within the upper 100 cm; pedons of Solonetz contained calcic horizons less than 100 cm from the surface; pedons of Solonetz contained calcisols; pedons of Regosols contained densic bedrock at 79 cm; and pedons of Leptosols comprised lithic bedrock at 41 cm.

Table (2): Soil salinity classes and their impacts on crops (according to Jehangir et al., 2013).

Soil salinity class	Saturated paste (dS/m)	Impacts on crops
Nonsaline	0-<2	All crops are suggested
Slightly saline	2-<4	Sensitivity crops are restricted
Moderately saline	4-<8	Many crops are restricted
Strongly saline	8-<16	Only tolerant crops are satisfactory
Very strongly saline	≥16	Only some very tolerant crops are satisfactory

Table (3): The soil mapping units and reference soil groups (RSGs) distributed on the landforms of the Wadi Wardan region.

Landform	Slope position	Soil types		Areal coverage (km^2)
		Soil mapping unit (SMU)	RSGs as per WRB soil taxonomy	
• Coastal plain (21 km^2)	Toeslope and lowland	SMU1: Very deep, coarse textured, very strongly saline, moderately calcareous soils.	Calcaric **ARENOSOLS** (Salic)	21 km^2
• Wardan's delta (51.5 km^2)		SMU2: Deep, moderately fine textured, strongly saline, slightly calcareous soils.	Haplic **SOLONCHAKS** (Loamic)	51.5 km^2
• Wardan's delta (32 km^2) • Fluvial plain (11 km^2)	Footslope to toeslope	SMU3: Deep, fine textured, strongly saline-sodic, moderately calcareous soils	Yermic Salic **SOLONETZ** (Clayey)	43 km^2
• Wardan's delta (3.5 km^2) • Fluvial plain (36.2 km^2)	Footslope to toeslope	SMU4: Moderately deep, moderately coarse textured, nonsaline, strongly calcareous soils	Haplic **CALCISOLS** (Loamic)	39.7 km^2
• Fluvial plain (6.8 km^2) • Pediment (35.7 km^2)	Backslope to footslope	SMU5: Moderately deep, coarse textured, moderately saline, extremely calcareous soils	Calcaric Leptic **REGOSOLS** (Arenic)	42.5 km^2
• Pediment (69.3 km^2)	Shoulder (Upland)	SMU6: Shallow, coarse textured, nonsaline, extremely calcareous soils	Calcaric Coarsic **LEPTOSOLS** (Arenic)	69.3 km^2

Table (4) : Morphological characteristics of Wadi Wardan study area.

Soil type	Total depth (cm)	Root-Restricting Depth	Drainage	Elevation (MTL, m)	Slope gradient	Erosion degree	Flood hazard (Abdel-Lattif and Sherief, 2012)	Surface fragments
Arenosols	172	Salic horizon at a depth of> 100 cm.	Excessively Drained	3-9	0.6% (Nearly level)	Slight	High flood (>150 m^3/s)	None
Solonchaks	149	Salic horizon within 50 cm from the surface	Moderately Well Drained	6.38	0.7% (Nearly level)	Moderate		
Solonetz	138	Natric and salic horizons within the upper 100 cm	Poorly Drained	19-51	1.1% (Very gently sloping)	Moderate	Low flood (100-150 m^3/s)	Common coarse gravel
Calcisols	97	Calcic horizon at < 100 cm of the pedon surface	Somewhat Poorly Drained	30-89	1.9% (Very gently sloping)	Severe		Common to many cobbles
Regosols	79	Densic bedrock at 79 cm		104-245	4.8% (Gently sloping)	Extreme	Moderate flood (< 100 m^3/s)	Many stones
Leptosols	41	Lithic bedrock at 41 cm	Poorly Drained	125-263	9.3% (Sloping)	Extreme		Abundant stones and boulders

1 km^2 ≈ 238 Faddans or 247.1 Acres or 100 Hectares; MTL (Mean Tide Level, formerly Mean Sea Level).

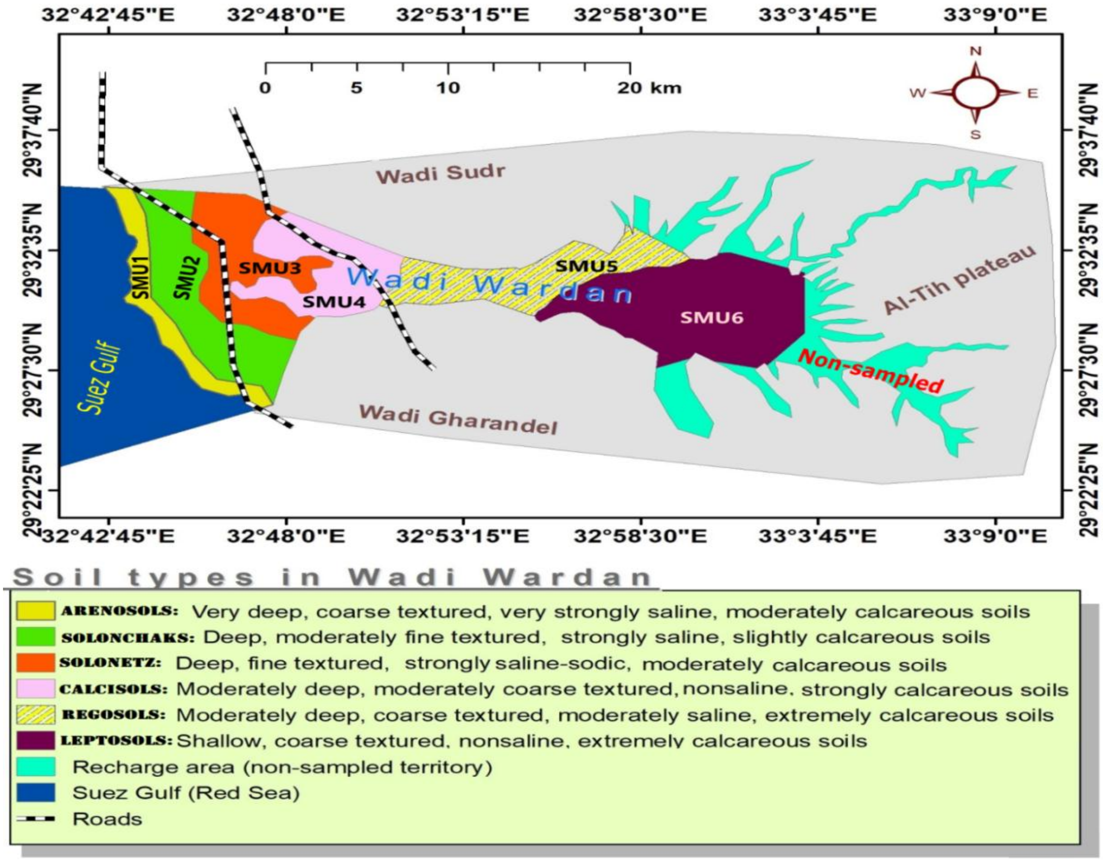

Fig. (9): Soil reference groups and mapping units in Wadi Wardan, South Sinai, Suez Gulf, Egypt.

Soil depth varied over Wadi Wardan, ranging from shallow (41 cm) at the shoulder to very deep (172 cm) at the toeslope. The rock fragments exhibit significant variation, ranging from 0.87% in the downslope to 45.12% in the upslope Leptosol C layer (Table 5). It exhibits an uneven vertical trend from topsoil to subsoil and an increasing horizontal trend from downslope to upslope (Fig. 10). The coarse texture soils predominated in the studied Wadi, which covered 105 km^2 of pediment, 6.8 km^2 of fluvial plain, and 21 km^2 of coastal plain. Moderately coarse textures were found in 39.6 km^2 of Wardan's delta (3.5 km^2) and fluvial plain (36.2 km^2) soils, whereas moderately fine textures were found in 51.5 km^2 of Wardan's delta soils. Fine textured soils were discovered in 43 km^2 (32 km^2 in Wardan's delta and 11 km^2 in the fluvial plain). According to Jehangir *et al.* (2013), saline soils were found in the examined soils of various types. Nonsaline soils were discovered in a large portion of the pediment plain (69.3 km^2), a minor part of Wardan's delta (3.5 km^2), and 36.2 km^2 of the fluvial plain. In contrast, very strongly saline soils were found only in the coastal plain (21 km^2), followed by strongly saline-sodic soils in Wardan's delta (32 km^2 of Wardan's delta; 11 km^2 in fluvial plain). Fig. 11 shows the patterns and distribution of soluble salts in soil pedons and across the toposequence under study. Due to salt elements being eroded from upslope lands into the downslope and seawater seepage, the soils of the Wadi Wardan delta and coastal plain were extremely salinized (Table 5; Fig. 11).The examined soils were classed as slightly calcareous, moderately calcareous, strongly calcareous, and extremely calcareous based on the $CaCO_3$ level and FAO (2006). The trend and distribution of lime vertically within the soil pedon and horizontally across the toposequence are presented in Fig. (12).

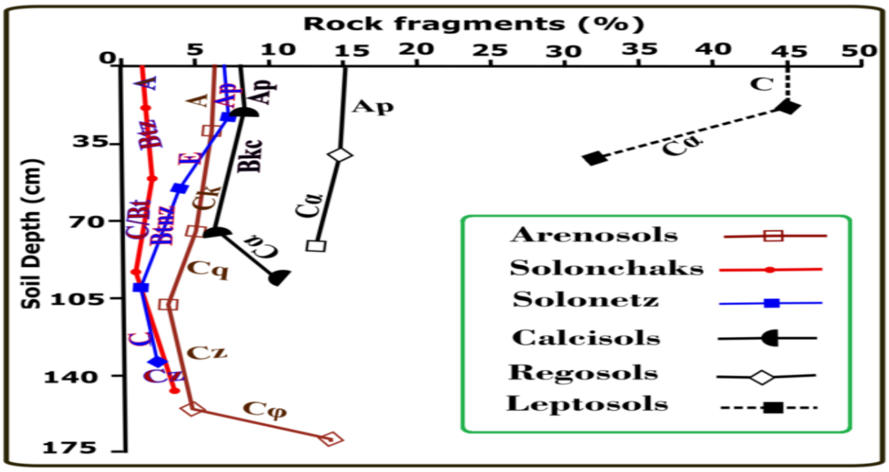

Fig. (10): A comparison of the rock fragments trends among pedons across the toposequence.

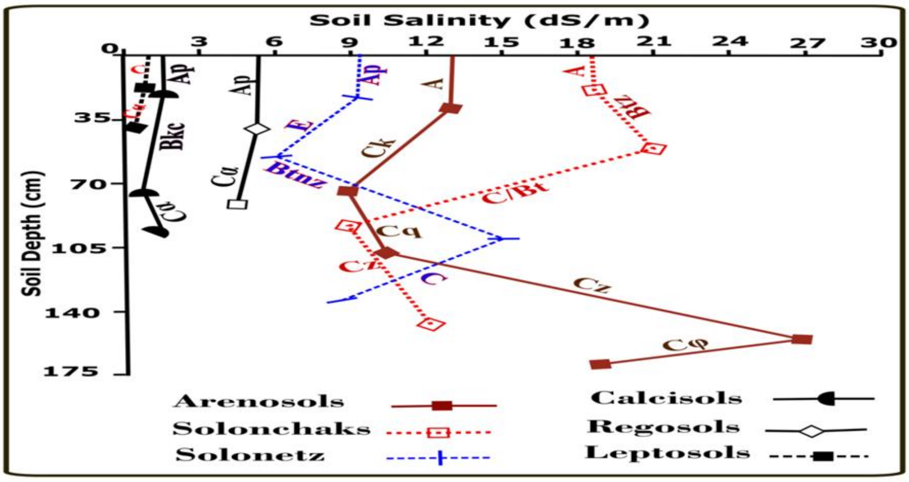

Fig. (11): A comparison of the soil salinity trends among pedons across the toposequence.

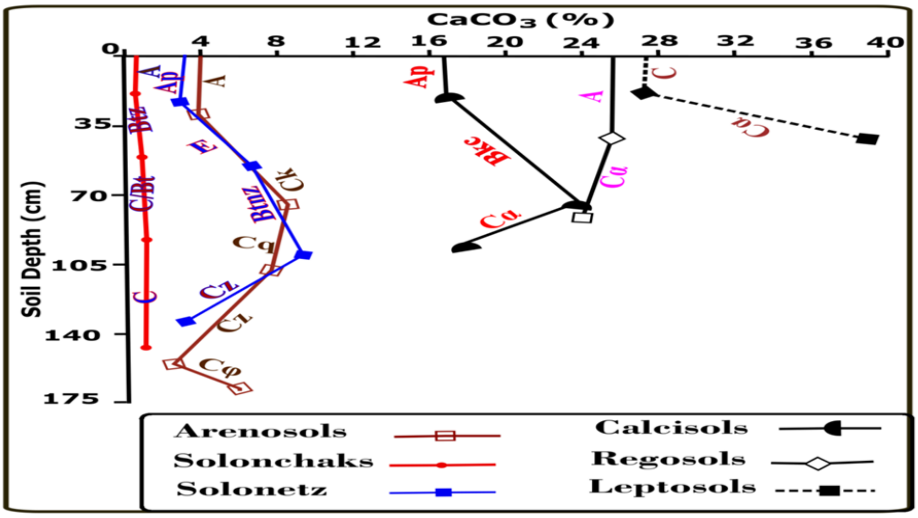

Fig. (12): A comparison of the lime content ($CaCO_3$ %) trends among pedons across the toposequence.

Horizon thicknesses and soil physiochemical characteristics differ across the toposequence and between horizons within the same pedon (Table 5). The representative pedon horizon sequences for each soil type are as follows: A-Ck-Cq-Cz- C for Arenosols; A-Btz-C/Bt-Cz for Solonchaks; Ap-E-Btnz-C for Solonetz; Ap-Bkc- C for Calcisols; A- C for Regosols; C- C for Leptosols. In the analyzed toposequence of Wadi Wardan, the shoulder landscape location had the thinnest regolith (41 cm), which might be related to increased soil erosion. Due to the migration of soil organic carbon (C_{org}) and its accumulation in the lowland, the surface horizons' soil color darkens downslope over the studied toposequence. The Munsell value was higher in coastal plain soils (5-7) (Arenosols), both Regosols (6-8) and Leptosols (7-8), and decreased in Solonchaks (2-4) and Solonetz (2.5-4) (Table 5). The soil color lightens in these soil types (Calcisols, Regosols, and Leptosols) as the $CaCO_3$ content rises and the C_{org} concentration falls in tandem. Darker colors are found in surface layers with more decomposed organic matter than in subsurface horizons with less decomposed organic matter (Tables 4 and 5).

In the higher landscape positions of the toposequence (the shoulder and backslope), the Regosols and Leptosols contain varying amounts of rock fragments. The subsurface Cα layer of regosols contains 13.45% of rock fragments, while the surface C layer of leptosols contains 45.12%. Comparatively, the rock fragments content at the lower positions (such as the toeslope and footslope) ranges from 14.35% in the Arenosols' lowest layer (Cφ) to 0.87% in the C/Bt horizon of Solonchaks (Table 5).

Soil compaction is indicated by bulk density. Soil processes and productivity are influenced by infiltration, rooting depth, water capacity, soil porosity, aeration, nutrient availability, and microbial activity (Suzuki *et al.*, 2022). The bulk density of soil is its oven-dry weight per unit volume at field moisture capacity or prescribed moisture content. However, soil ρb trended differently with depth for Arenosols at toeslope places. In these positions, soil ρb decreases with depth due to rising organic carbon concentration in sub-soil layers. Downslope soil ρb reduced from summit to toeslope, perhaps due to increased C_{org} content.

Soil texture and C_{org} are correlated with bulk density. Most rocks have a density of 2.65 g/cm^3. Ideally, silt loam should have 50% pore space and 1.33 g/cm^3 bulk density (Suzuki *et al.,* 2022). High organic matter content, well-aggregated, porous soils typically have lower bulk density, as observed in this study. Sandy soils (Arenosols, Regosols, and Leptosols) have a higher bulk density (1.61-1.81 g/cm^3) due to less pore space than silty or clayey soils. As soil depth increases, bulk density normally rises. Subsurface and deeper layers (Cφ, Cα, and Ck) in soil pedons contain less organic matter, aggregation, and root penetration than the surface layer (A or Ap), resulting in greater compactness and less pore space (Table 5).

Landscape position can affect the vertical distribution of C_{org} within each pedon, which may grow or decrease with depth. C_{org} concentration dropped with depth in lower Solonchaks, from 0.41% in the A horizon to 0.17% in the Cz horizon. Table 5 suggests the tendency may be due to the organic matter-rich surface layer and soil structure. Like the Solonetz, the C_{org} diminished with depth at footslope landscape places. However, C_{org} content increased significantly with shoulder depth in Regosols and Leptosols. Deposition of degraded inorganic elements from neighboring uplands and surface strata may explain this rising tendency (Table 5). Eroding soil materials from the upland and depositing them in the lowland may explain the significant rise. C_{org} declined with depth vertically within pedons, likely due to the decrease in organic matter and the tight correlation between C_{org} and soil texture.

ASi extracted with distilled water followed C_{org} from shoulder to toeslope landscape positions. For instance, ASi was 1235 mg kg^{-1} for the A horizon at the toeslope and 279 mg kg^{-1} for the surface horizon at Solonetz (Table 5). Erosion may have moved soluble Si from upland to lowland. C_{org} and ASi pedons had unique vertical distribution. ASi concentration increased with pedon depth except in the

Table (5): Soil characteristics of the dominant pedons for each soil type at Wadi Wardan.

Soil type	Horizon designation	Horizon thickness (cm)	Munsell value	Rock fragments (%)	Soil Texture	C_{org} (%)	ESP (%)	pH	EC_e (dS/m)	$CaCO_3$ (%)	Gypsum (%)	ASi (mg/kg)	Soil ρb (g/cm^3)
Arenosols (SMU1)	A	31	7	6.01	COS	0.12	5.26	8.19	13.5	4.2	0.34	1235	1.67
	Ck	42	6	5.32	LFS	0.19	3.65	7.96	9.3	9.6	1.02	2103	1.63
	Cq	33	7	3.45	LCOS	0.17	6.04	8.35	11.7	8.5	0.65	957	1.61
	Cz	47	5	5.41	LFS	0.20	4.32	8.44	27.9	3.7	4.47	904	1.64
	Cφ	19	7	14.35	LVFS	0.03	3.07	8.73	19.6	6.4	0.31	1671	1.81
Solonchaks (SMU2)	A	17	3	1.34	SCL	0.41	7.32	7.99	19.3	0.2	3.24	523	1.51
	Btz	34	2	2.04	CL	0.30	6.32	7.86	21.1	0.6	0.35	694	1.57
	C/Bt	43	3	0.87	SCL	0.25	1.65	8.35	9.1	1.3	4.03	832	1.62
	Cz	55	4	4.32	SiCL	0.17	3.54	7.95	12.5	1.0	1.08	1021	1.63
Solonetz (SMU3)	Ap	25	4	6.07	SiC	0.24	13.65	8.91	9.1	3.6	0.19	343	1.51
	E	32	3	4.01	SC	0.19	15.04	9.15	6.0	7.3	0.47	593	1.57
	Btnz	43	2.5	1.32	C	0.04	21.65	9.34	15.9	9.0	1.32	747	1.75
	C	38	4	2.35	SiC	0.17	9.48	9.09	8.7	4.3	1.07	820	1.63
Calcisols (SMU4)	Ap	21	5	7.12	COSL	0.21	4.57	8.73	1.8	17.3	0.62	432	1.59
	Bkc	52	4	6.35	FSL	0.07	5.36	9.12	0.9	24.9	1.04	593	1.67
	Cα	24	6	11.04	SL	0.15	2.09	8.94	1.2	18.3	1.19	732	1.73
Regosols (SMU5)	A	37	8	15.32	S	0.09	3.65	8.76	5.5	26.3	1.74	653	1.65
	Cα	42	6	13.45	LFS	0.11	5.49	8.64	4.1	34.0	0.24	736	1.71
Leptosols (SMU6)	C	17	8	45.12	COS	0.03	2.04	8.55	1.2	27.6	0.41	279	1.62
	Cα	24	7	32.14	FS	0.07	5.11	8.94	0.6	39.3	0.39	531	1.78

Explanations: Designations of horizon/layer with master symbols and suffixes as per IUSS Working Group WRB (2022), C/Bt (Bt horizon forming lamellae within a C layer), α (Primary carbonates presence); φ (Fe and/or Mn Accumulation); C_{org} (Soil organic carbon); ASi (Amorphous silicon was extracted with HCl and KOH mixture); ρb (Bulk density); S (sand); COS (coarse sand), LCOS (loamy coarse sand), LFS (loamy fine sand), LVFS (loamy very fine sand), F.S. (fine sand), SCL (sandy clay loam), SiC (silty clay), S.C. (sandy clay), C (clay).

toeslope landscape position (Histosol), where it fluctuated (Table 5). ASi concentration increases with depth in upper landscape positions, perhaps because to soluble Si translocation. Erosion may raise surface horizon ASi concentration at the lowland. Eroded organic and inorganic elements from the upland to the lowland may explain this.

Throughout the toposequence, pH is typically alkaline and varies with depth (Fig. 5). The pH in Solonetz pedons increased (8.91-9.34) with depth and decreased at the lowest layer (C). The Btnz horizon has the greatest pH (9.34), ESP (21.65%), and E.C. (15.9 dS/m) values, indicating saline-sodic soils.

Management of High Bulk Density in Studied Soils

The bulk densities of Regosols, Leptosols, and Calcisols are high and vary from 1.59 g/cm^3 for Clacisols to 1.78 g/cm^3 for Leptosols. Leptosols comprise exceedingly thin soil layers over continuous rocks and exceptionally rich layers of coarse fragments. They are especially prevalent in areas with mountains. They might be used as forest land and as a resource for grazing during the wet season. Drastic conditions can arise even in humid environments due to the shallow depth of many Leptosols and extensive internal drainage. Regosols are mineral soils with extremely low development in unconsolidated materials that lack diagnostic horizons. Little profile development results from an early age and sluggish soil formation, such as aridity. Regosols are of little agricultural value in desert regions because they have a depth less than 100 and are rich with gravel or rock fragments. There are a lot of Regosols used for heavy grazing.

The study soils have high bulk density for several causes, such as low organic carbon and horizon development with cementing agents. Management strategies can modify bulk density by affecting soil cover, organic matter content, structure, compaction, and porosity (Suzuki *et al.,* 2022). Excessive tillage degrades soil organic matter and decreases aggregate stability, making them vulnerable to water and wind erosion. When degraded soil particles fill pore spaces, porosity decreases, and bulk density rises. Tillage and machine use create compacted soil layers with higher bulk density, such as plow pans. Tilling before planting leads to a temporary decrease in surface layer density. Compaction of soil occurs due to farm machine excursions, rainfall, animal trampling, and other disturbances (Reichert *et al.,* 2018). Organic matter enhances soil water retention, both directly and indirectly. Increasing organic matter and minimizing compaction can reduce bulk density and porosity. No-till, cover crops, manure, compost, and diversified rotations with high-residue crops and perennial legumes or grass can assist. Avoid soil disturbance and damp equipment. Use equipment only on designated roadways or between rows. Use multi-crop systems with varying rooting depths to loosen compacted soil.

Management of Arenosols

Arenosols are deep sandy soils located on the research area's toeslope. These soils were developed in residual sands after in situ weathering quartz-rich sediments or rock and recently deposited sands in desert dunes and coastal areas. Arenosols have diverse habitats, resulting in varying agricultural applications. All Arenosols share a coarse texture, leading to high permeability and low water and nutrient storage capacity. Conversely, Arenosols simplify root and tuber crop cultivation, rooting, and harvesting. In dry and semi-arid locations with annual rainfall below 300 mm, Arenosols are extensively grazed. Over 300 mm of annual rainfall allows dry farming. Arenosols have poor coherence, nutrient storage, and erosion sensitivity in researched soils. Irrigated Arenosols produce high yields of small grains, melons, pulses, and feed, but percolation losses may limit surface irrigation. Combining drip or trickle watering with proper fertilizer dosage may help resolve the issue. Many Saharan locations with Arenosols have limited vegetation on their soils. Without proper soil protection measures, uncontrolled grazing and clearance for crops can destabilize soils and cause shifting dunes.

Management of Calcisols

Calcareous soils containing a calcic horizon (known as Calcisols) are extensively found in arid and semi-arid regions, covering approximately one-third of the Earth's land surface. The present study analyzed the distribution and properties of calcareous soils, as depicted in Fig. 12. The constraints of Calcisols for crop cultivation arise from the existence of calcic layers containing elevated amounts of $CaCO_3$ in the soil parent material, leading to the accumulation of free CaCO3 in the soil profile. It is important to adhere to sustainable management strategies to address crop yield limitations in Calcisols. The pH of these soils typically exceeds 7; in the presence of free sodium carbonate, it can surpass 9 (Alessandrino *et al.,* 2022). Certain soils may contain concentrated deposits of free $CaCO_3$, forming dense layers called ‘caliche’. These layers are impervious to water infiltration and hinder the penetration of plant roots. Calcisols can be primarily composed of free $CaCO_3$, but they can also contain substantial quantities of iron (Fe), aluminum (Al), and manganese (Mn). These elements may exist as separate minerals or as coatings on soil particles such as clay, sand, and silt.

Additionally, they can be bound to soil organic matter in complex forms. The primary limitations on agricultural productivity in calcareous soils include deficiencies in phosphorus and trace elements such as iron, zinc, and copper, as well as the formation of surface crust and an impermeable subsurface compact layer. The limitations on soil productivity in Calcisols can be resolved through the careful selection and positioning of fertilizers, the introduction of organic matter to encourage the formation of stable aggregates that prevent dispersion and resist the formation of crust, and the implementation of deep ripping to penetrate the compacted pan layer, thus enabling roots to access water and nutrients present beneath this layer (Paraguassú *et al.,* 2022).

Management of Solonchaks

In the Wadi Wardan study region, the soils of Solonchaks cover an area of 51.5 km^2. Solanchaks in study soils contain significant soluble salts at certain times of the year. Solonchaks are found in coastal regions in all climates, particularly in arid and semi-arid settings. Common international names include Saline soils and Salt-affected. In Wadi Wardan, a semi-arid environment, groundwater rises to the upper soil, and irrigation sites are poorly managed. Many Solonchaks have gleyic characteristics at some level, ranging from weak to heavy weathering. Salt accumulation is highest near the soil surface in low-lying places with shallow water tables (Solanchaks). Internal Solonchaks, where groundwater does not reach the topsoil, have the highest salt deposition below the soil surface.

Two ways excess salt in Wadi Wardan soil affects plant growth (Jehangir *et al.,* 2013): Salt-dissolved electrolytes exacerbate drought stress by affecting plant water intake through osmotic potential. Plants must balance matrix potential and osmotic potential to absorb soil water. Salts alter soil solution ion balance due to reduced nutrient availability. The antagonistic effects of Na, Ca, and Mg on K are recognized. Salts can poison plants in large doses. Because they affect N metabolism, Na and chloride ions are especially harmful. Agricultural soil with excessive salt content is useless. They were leaching salts from the soil to prevent it from being Solonchaks for good yields. In addition to crop needs, irrigation water should be applied above the required amount to sustain soil water flow and drain salts from the root zone. Crop irrigation in arid and semi-arid regions requires drainage to keep groundwater below critical depth. Gypsum to reduce sodium and alkalinity. It affect hydraulic conductivity (Zhen *et al.,* 2023).

Management of Solonetz

Solonetz covers 43 km^2 in Wadi Wardan. Solonetz are Saline-sodic and have a dense, clayey subsurface horizon (Btnz) with high Na^+ and Mg^{++} ion adsorption. Solonetz with free soda

(Na_2CO_3) is highly alkaline (pH > 8.91; ESP: 9.48-21.65%) (Table 5). Solonetz amelioration involves two main components: increasing soil porosity and reducing ESP. Saline-sodic soil contains high levels of soluble salts and exchangeable Na^+, which can affect all agricultural plants. Saline-sodic soils with EC_e > 4 dS m^{-1}, pH > 8.5, and ESP > 15. Some literature refers to soils with excess exchangeable Na^+ as "alkali" instead of "sodic" (Semenkov and Konyushkova, 2022). Therefore, "saline-alkali" is used instead of "saline-sodic," and "alkali" is used instead of "sodic". However, the term "alkali" is avoided due to its ambiguity with "alkaline" soils (pH > 7.0) (Jehangir *et al.,* 2013). Globally, salt-affected soils are prevalent in arid and semi-arid climates in over 100 nations. These soils cover approximately 25% and 60% of the world's irrigated and farmed land. About 62% of salt-affected soils worldwide are saline-sodic/sodic, while 38% are saline (Semenkov and Konyushkova, 2022).

Gypsum is often added to soil to start reclamation. Deep ploughing may eliminate costly amendments when gypsum is shallow. Under traditional restoration methods, na-resistant Rhodes grass is planted to increase soil permeability progressively. After building a pore system, high-quality (Ca-rich) water leaches Na ions from the soil, avoiding clear water, which can worsen dispersion. One extreme reclamation method dissolves $CaCO_3$ in soil using diluted sulfuric acid, a metallurgical waste product. This condition replaces exchangeable Na with Ca^{++} ions in soil solution. It improves soil aggregation and permeability (Green *et al.,* 2023).

Reclamation of Salt-affected Soils

There are many ways to restore salty soils. The effectiveness of treatments depends on factors such as soil physicochemical, mineralogical features, drainage, climate, salt content, leaching water quality, groundwater quality, exchangeable Na^+ replacement rate, lime/gypsum presence, amendment availability, tillage equipment, local crops, topography, and reclamation timeframe. For successful reclamation, soil drainage, land leveling, and deep groundwater below 3 meters are essential. Salt-affected soils in Wadi Wardan are classified as saline (Solonchaks) or saline-sodic (Solonetz). To recover soluble salts from saline soils, use high-quality irrigation water to leach into deeper soil layers (Green *et al.,* 2023). The amount of water used varies on soil type, salinity, wetness, and application tactics. Soil reclamation often needs high-quality irrigation water. Soluble Ca^{2+} sources like gypsum and high-quality irrigation water may be added to remediate saline-sodic soils. In leaching water, Na^+ ions on the exchange complex are replaced by Ca^{2+}, and dissolved salts are eliminated from the root zone. Water must flow through the soil profile to reclaim saline (Solonchaks) and saline-sodic soils (Solonetz). Reclamation methods for saline-sodic soils (Solonetz) include physical, chemical, biological, hydro technical, electro-reclamation, and synergistic procedures. Sodic soils (Solonetz) have lower porosity from slaked and scattered particles (Semenkov and Konyushkova, 2022). A successful amendment boosts porosity, hydraulic conductivity, and infiltration rate and lowers bulk density. By introducing more Ca^{2+} than Na^+ to soil solution and exchange sites, reclamation procedures can improve the physical properties of sodic soils (Green *et al.,* 2023).

Physical treatments improve salt-affected soils, including deep plowing, subsoiling, hauling, sanding, and horizon mixing. Deep ploughing is 40-150 cm deep. This approach works on layered impermeable soils. As demonstrated by tests, a single 40-75 cm deep ploughing enhances the physical and chemical properties of calcareous sodic soils (Calcisols) cost-effectively. If subsurface soil is more sodic than surface soil, avoid deep ploughing. High-dose gypsum application benefits subsoils by enhancing the soil reclamation process. Tractors with high power drag steel/iron strips (knives/tines) 60-90 cm apart as sub-soilers. Open soil channels increase permeability. Sub-soiling benefits persist for years due to lime layer disintegration. One season without lime layer disintegration is beneficial. Sanding permanently alters soil texture. Increasing root penetration, water, and air permeability promotes salt drainage from the root zone. For optimal results, mix sand with 10 cm surface soil. Hauling replaces salt-affected soil with high-quality soil. Hauling has benefits but may be excessively costly. Horizon mixing is utilized for soil profiles with a good surface but a poor lower horizon. Saline-sodic soils have a favorable surface soil, a slowly permeable sodium-affected B horizon, and a more permeable gypsum horizon (Semenkov and Konyushkova, 2022). Mixing profiles maintains surface soil and improves subsoil and substratum. The upper surface is removed, the subsoil and substratum are combined, and the surface is reconstructed.

Chemical additions improve soil and crop growth. For soil Na^+ restoration, chemical additions are chosen based on availability, cost, handling, application, and response time (Semenkov and Konyushkova, 2022). Most saline-sodic/sodic soil rehabilitation chemical additions fall into three categories: Soluble $CaCl_2$, mined gypsum, and high-analysis phosphatic fertilizer phosphor-gypsum. These supplements convert $CaCO_3$ to soluble $CaSO_4$, $Ca\ (HCO_3)_2$, $Ca(NO_3)_2$, or $CaCl_2$ to mobilize Ca^{2+} in calcareous soils (Calcisols). Normal and salt-affected soils need organic matter for physical, chemical, and fertility improvements. Green manures, farm manures, poultry manures, and slaughterhouse waste are employed. Reclaiming sodic soils may benefit from organic polymers. Limited availability and slow reaction rates limit the use of molasses meal from the sugar industry to remediate saline-sodic soils. Growing crops in salt-affected soil is called "biological reclamation". The same phrase applies to adding organic matter like farm yard and green manure to salt-affected soils. Manures and other organic materials should be employed separately to distinguish organic from biological additions for reclaiming sodic/saline-sodic soils. Underground plant-root contact profoundly impacts soil conditions. Roots can lower oxygen levels, release organic compounds, produce chelating and reducing chemicals, increase CO_2 partial pressure, establish solution flow channels, boost microbial processes, and change soil physical and chemical properties. Above-ground plant parts cover soil, reduce warmth, improve mulching, decrease evaporation, and reduce capillary rise, inhibiting salt transfer (Han and Niles, 2023).

Control flood water and never disseminate excess irrigation water in the irrigated region. Limited seepage is required. In locations without lined canals and water systems, losses might reach 45%. Lining canals and water courses is crucial to minimize conveyance losses. Initial success can be achieved by covering with clay materials. Not all traditional irrigation systems have been reconstructed. Canals may be overly long, lack hydrotechnical equipment, or are meandering. Reconstructing these systems is necessary to meet present agricultural needs. To prevent seepage, avoid using irrigation canals for domestic water delivery during non-irrigation periods. Special canals, storage ponds, or wells must be built to achieve this.The lands must be carefully leveled under conditions where surface irrigation methods are used. This practice improves water-use efficiency (Han and Niles, 2023).

Management Strategies for Salt-affected Soils

Balanced fertilization and saline agriculture are the main management strategies for controlling salt-affected soils (Weil and Brady, 2016). To manage salt-affected soil, consider leaching needs, crop selection, irrigation, fertilization, and planting practices. Choosing crops with 50% lower yields on salt-affected soils can impact management performance, particularly during early colonization. Salt tolerance refers to a plant's ability to grow despite soil salinity in the root zone. Assessing plant salt tolerance potential involves evaluating their survival ability in salt-affected soils. Crop yield on salt-affected soils is typically 50% lower, and crop output is lower than normal soil under identical conditions (Semenkov and Konyushkova, 2022). The salt tolerance of plants is not a precise value. Environmental elements (soil fertility, physical condition, salt distribution, irrigation, climate) and biological factors (growth stage, cultivars, rootstocks) impact it.

Balanced fertilization

Salt, sodicity, and their combination decrease soil nutrients. Sodic and saline-sodic soils often have excess Na^+ and nutritional deficiencies. High pH and poor physical features, such as Na^+ dominance and dispersed soil matrix, cause limited nutrient mobility in sodic soils. Crop performance relies on fertilizer management. Low organic matter and nitrogen shortage characterize salt-affected soils. Sesbania species can be utilized for green manuring to mitigate nitrogen shortages and salinity/sodicity hazards. Sodic and saline-sodic soils have higher phosphorus availability due to higher Na_2CO_3 concentrations generating soluble Na_3PO_4. Research indicates sodic soils may need less P fertilizer after restoration (Wallander *et al.*, 2021). Research indicates a 50% reduction in P dose for rice-wheat rotations during reclamation for up to three years without yield loss. High sodicity levels might result in low soil Ca^{2+} levels. Fertilizers with Ca^{2+} (calcium nitrate, single superphosphate) or physiological acidity (ammonium sulfate, urea) outperform Ca-free or less acidic compounds like NH_4NO_3. Marginal salt-affected soils require 15-30% more fertilizer than normal soils in any agroecological zone, excluding P-containing fertilizers. Modifying planting procedures can reduce salt accumulation around seeds and increase germination for sensitive crops (Semenkov and Konyushkova, 2022).

Saline agriculture

Saline agriculture utilizes genetic resources (plants, animals, fish, insects, and microbes) and enhanced agricultural processes to sustainably and profitably utilize saline soil and irrigation water. Saline agriculture strategically uses salt-tolerant crops, genotypes, grasses, trees, and shrubs to utilize salt-affected soils (Uniyal *et al.* 2020). Site-specific components of this system adapt to farmer demands, land capability, locale, market availability, and climatic circumstances. Despite regional variability, salt-affected soils could be productive. Crops that tolerate salt are grown on slightly salty terrain (Table 6). The moderately salt-affected grounds for salt-tolerant trees and grasses and extremely salt-affected lands for salt-tolerant shrubs and bushes are suggested (Weil and Brady, 2016).

The world has about 1,500 salt-tolerant plant species. Major crops such as rice, wheat, cotton, and maize have varying saline tolerance and associated issues (Uniyal *et al.* 2020) (Table 6). Major crops grow little or not at EC_e 15 dS m^{-1}. Genetic differences exist among crop varieties. Rice with moderate salt tolerance yields 30-35% more paddy than regular types. Rice is the only crop that thrives on waterlogged and sodic soil. Wheat cultivars with salt tolerance include SARC-I, SARC-II, SARC-III, SARC-IV, SARC-V, and SARC-VI. Cotton, a salt-tolerant crop, faces emergence issues in sodic or saline-sodic soils (Wallander *et al.,* 2021). NIAB-78 and MNH-93 are ideal salt-tolerant cotton cultivars. Salt-tolerant plants and grasses include date palm, sugarbeet, semidwarf wheat, Bermuda grass, mesquite, and river saltbush. Some salt-tolerant plants can grow quickly with electrical conductivity ECe $\geq$30 dS m^{-1}. Other salt-tolerant plants for saline agriculture, according to Weil and Brady (2016), include sugar beet, fig, guar, oats, papaya, rape, sorghum, soybean, Rhodes grass, and Cynodon dactylon species (Table 6).

Soil Management Framework and Future Directions

In Wadi Wardan of South Sinai, soil resource management affects soil ecosystem service value, devaluation, degradation, maintenance, and enhancement (Fig. 13). Despite short-term profits from crop production, this type of management is unsustainable and causes soil disservices like soil erosion, water pollution, greenhouse gas emissions, habitat and biodiversity loss, and water and nutrient loss (Gashaw *et al.*, 2021). Conventional tillage, short crop rotations, herbicides and pesticides, and industrial animal farms are known to harm agricultural soil ecosystem services (Afroz *et al.*, 2021). Pesticides, synthetic fertilizers, and intensified agricultural practices degrade soil ecosystem functions. Due to high soil disturbance, these practices can cause pollution, alkalization, salinization, erosion, compaction, and water and nutrient loss. Deteriorating soil ecosystem services negatively impact production, and restoration might be expensive, further devaluing them (Ricci *et al.* 2020). However, intensive farming has far-reaching effects beyond the economy and environment. Salinity agriculture, conservation tillage, organic farming, cover crops, crop diversity, deep ploughing, soil amendments, soil drainage, balanced fertilization, and precision farming can improve soil ecosystem services over time. These methods promote or maintain soil ecosystem services. These eco-friendly business practices protect soil biodiversity and bring physical and intangible economic benefits to the Wadi Wardan study region (Fig. 13).

Future proposals could include an integrated framework to codify an adoption spectrum for sustainable agriculture management based on Fig. (13) and multidimensional adoption viewpoints (Thompson *et al.,* 2021). The framework should examine four elements: completeness, diversity, sophistication, and longevity (Fig. 14). Full adoption of an innovation is called entirety. The entireness of an innovation is measured by its present adoption and the amount of adoption across a farm, community, or region, depending on the scale studied. Innovation variants are considered while calculating variability. Farmers may employ organic fertilizers alone or with animal dung and biological fertilizers (Wallander *et al.*, 2021). Adoption longevity recognizes that technology or innovation may be rejected after use. Finally, sophisticated adoption involves merging complementary approaches or re-inventing innovations for added functionality and benefits (Rudnick *et al.*, 2021). For instance, farmers can use livestock grazing to harvest cover crops as supplementary revenue crops instead of incorporating them into fields (Berihun *et al.*, 2020). These four adoption components can help identify complex processes, understand farmer typologies, and align technical assistance and policy design for sustainable soil management and agricultural innovations.

The framework for cover crop adoption offers an organized approach to understanding sustainable agriculture practices. It offers potential for growth and study due to its current limits. Our respondents have a higher cover crop adoption rate than previously reported national statistics (Wallander *et al.*, 2021), possibly due to nonresponse bias. As a result, our method may over-represent innovators and adopters while under-representing non- and previous adopters. A paradigm for sustainable agriculture management that prioritizes completeness, diversity, sophistication, and longevity may be included in future recommendations (Fig. 14; Han and Niles, 2023).

Table (6): Salt-tolerant plants in each type of studied soil.

Crop type	**Sensitive crops (0-4 dS/m)**	**Moderately tolerant crops (>4-6 dS/m)**	**Tolerant crops (>6-8 dS/m)**	**Highly tolerant crops (>8-16 dS/m)**
	Almond	Corn	Rice t tolerant species	Barley, cotton, olive , rye
	Bean	Grain Sorghum	Oats, Figs	Sugar beet, guar,
	Clover	Lettuce	Pomegranate	rape,
	Onion	Soybean	Sunflower	Wheatgrass, rhodes grass
	Potato	Tomato	Wheat	Papaya, Cynodon dactylon
Soil type	Calcisols	Regosols	Solonetz	Solonchaks

Source: Weil and Brady (2016); Uniyal *et al.* (2020).

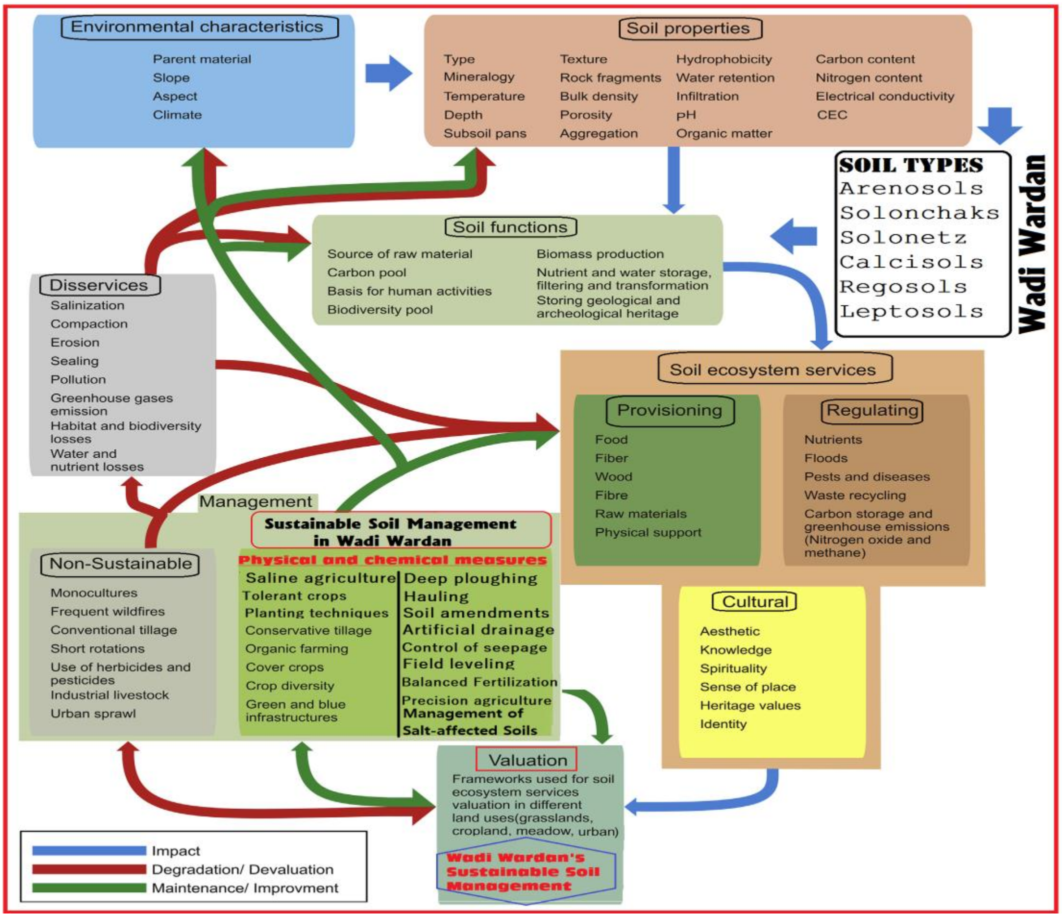

Fig. (13): Proposed sustainable management framework for soil ecosystem services in Wadi Wardan.

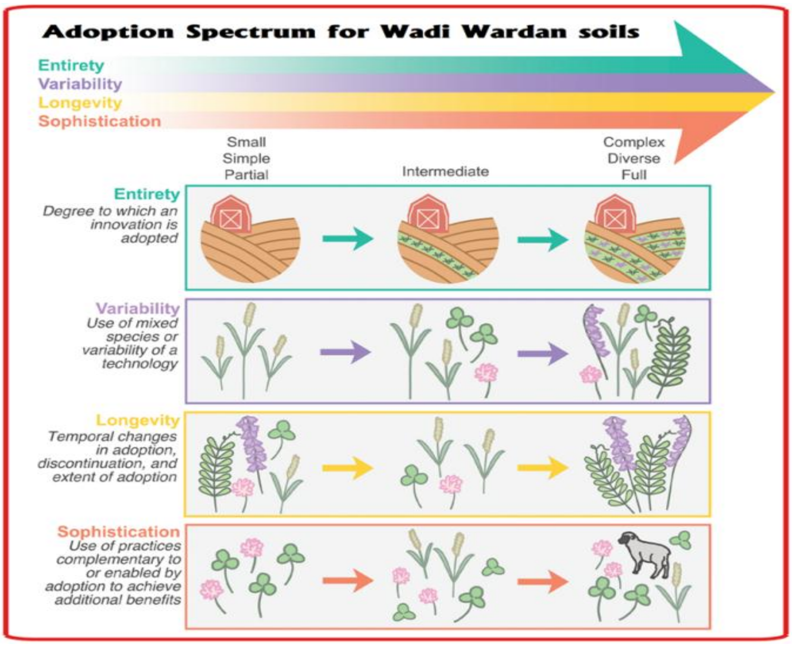

Fig. (14): A demonstration of the four principles of sustainable soil practices as future direction for soil resources management (Han and Niles, 2023).

CONCLUSION

The soil resources of Wadi Wardan (300 km2) in South Sinai were investigated. From upslope to downslope, primary landforms were discovered. The 33 km^2 recharge area of Wadi tributaries was not sampled. Pediment (105 km^2), fluvial plain (54 km^2), Wardan's delta (87 km^2), and coastal plain (21 km^2) were the landforms tested. Only four landforms in Wadi Wardan had 89 pedons distributed evenly among them. Soils range from shallow to deep, and drainage conditions vary. The soils studied ranged from coarse to fine. Upslope soils are nonsaline, while downslope soils are highly saline. The soils range from mildly to extremely calcareous. High b values and low organic carbon levels in Wadi Wardan indicate soil issues. Vertical root-restricting layers were discovered at various depths in the soil profile, as shown in Table 4. Soil pedons had excessive salts and a salic horizon at depths above 100 cm, Solonchaks had a salic horizon within 50 cm, Solonetz had natric and salic horizons within the upper 100 cm, Solonetz had calcic horizons less than 100 cm from the surface, Solonetz had calcisols, and Regosols had densic bedrock at 79 cm. Six mapping units were created based on soil depth, texture, salt content, and lime content. Soils in the pediment and river plains are mostly Leptosols (69.3 km^2), Regosols (42.5 km^2), and Calcisols (39.7 km^2) in the WRB soil taxonomy, while those in Wardan's delta are Sololnetz (43 km^2) and Solonchaks (51.5 km^2). Coastal plain soils (21 km^2) are Arenosols.

Egypt's food security is threatened by soil salinization as occurred in the study area. Several natural and human-induced processes contribute to soil salinization, and socioeconomic and political factors frequently play a significant role in accelerating the process. Often, these variables are beyond farmers' control and require policymakers' attention. Governments must implement policies and corrective measures to prevent soil salinization and rehabilitate impacted soils.

There are several proven technologies for reclaiming and managing salt-affected soils on farms. The efforts of government agencies and farmers to reclaim and rehabilitate salt-affected soils in the country have proven promising. To reclaim 115.5 km^2 of salt-affected soils (Solonchaks, Sololnetz, and Arenosols), stakeholders must collaborate to achieve the goal. Site-specific restoration programs should be designed and implemented in mission mode, with genuine engagement from local farmers. Farmers should be incentivized, not subsidized, to take corrective actions. Since urbanization is reducing cultivable land, restoring and managing salt-affected soils can enable land growth and improve food security in the country.

Soil and water salinity/sodicity threaten irrigation. The salinized and sodicated land in Wadi Wardan, south Sinai, Egypt, diminishes crop yield. Salty soil is classified as saline (Solonchaks), saline-sodic, or sodic. Leaching with high-EC water without amendment can rehabilitate saline soils in the first phase. Saline-sodic soils need Ca-amendment; gypsum works best. Mined gypsum is less soluble than industrial gypsum, which aids in the retention of electrolytes in these soils. Acids or acid formers can repair soils quickly but at a high cost. Saline agriculture cultivates salt-tolerant plants to control soil salinity/sodicity. Mulching, tillage, green manuring, and seedbed preparation, in addition to reclamation, are beneficial.

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الإدارة المُستدامة لموارد التربة بوادي وردان، إقليم خليج السويس، جنوب غرب سيناء، مصر

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الملخص العربى

تتدهور موارد الأراضي في مصر بسبب سوء إدارة التربة في ظل التوسع السكاني المتزايد. تسلط هذه الحالة الضوء على أهمية إدارة الموارد الأرضية بصورة فعالة لتلبية إحتياجات الغذاء المتزايدة من الشعب المصري. تهدف هذه الدراسة إلى إنتهاج إدارة مُستدامة للموارد الأرضية بوادي وردان بمنطقة خليج السويس، جنوب سيناء، مصر؛ وذلك طبقاً لكل نوع تربة، مع الحفاظ على استخدام الأراضي وإنتاج المحاصيل بحد أقصى وتجنب تدهور التربة. يمتد وادي وردان على مساحة ٣٠٠ كم^{٢}، كما يحتوي على موارد تربة واعدة زراعياً في جنوب سيناء حيث تعزيز استخدام الأراضي وإنتاج المحاصيل مع تجنب تدهور التربة. تم تحديد خمسة أشكال أرضية عبر وادي وردان من الأعلى إنحدارا وإرتفاعاتً إلى الأسفل إنحداراً، وهي كالتالي: روافد وادي وردان (٣٣ كم^{٢}؛ غير ممُثلة بقطاعات التربة)، المنحدرات Pediment (١٠٥ كم^{٢})، السهل الرسوبي النهري Fluvial plain (٥٤ كم^{٢})، دلتا وادي وردان Wardan's delta (٨٧ كم^{٢})، والسهل الساحلي Coastal plain (٢١ كم^{٢}). كما تم توزيع ٨٩ قطاع تربة على أربعة أشكال أرضية بوادي وردان بنسبة متناسبة مع اللمساحة بكل شكل أرضي. أوضحت الدراسة أن التربة تحت الدراسة تتروا‌ح من القطاعات الضحلة إلى العميقة، مع ظروف تصريف Drainage سيئة إلى جيدة. قوام التربة تراوح من الرملية الخشن إلى الطينية الناعمة غير ملحية كما بأراضي المنحدرات الصاعدة Upslope إلى شديدة التأثر بالأملاح كما بالمنحدرات الهابطة Downslope . وبناءً على قيمة pH، فقد وجدت التربة طفيفة القلوية إلى شديدة قلوية. أشارت نتائج الدراسة إلى إرتفاع قيم الكثافة الظاهرية ρb مع مستويات الكربون العضوي المنخفضة والتي تنذر بمشاكل تتعلق بتدهور الصفات الفيزيائية للتربة بوادي وردان والتي تتطلب إدارة مناسبة. تم التعرف على ست وحدات خرائطية Soil mapping units بناءً على عمق التربة الفعال وقوامها ومحتوى الملح والجير بها. وبناءً على تصنيف WRB لتقسيم اللتربة، فقد تم تصنيف معظم التربة في المنحدرات Pediment والسهول النهرية Fluvial plains كـ لبتوسول Leptosols (٦٩.٣ كم^{2})، ريجوسول Regosols (٤٢.٥ كم^{2})، وكالسيسول Calcisols (٣٩.٧ كم^{2})، بينما تحتوي دلتا وادي وردان على نوعين من الأراضي هما Sololnetz (٤٣ كم^{2}) Solonchaks (٥١.٥ كم^{2}). كما وصُنفت التربة في السهول الساحلية على أنها Arenosols (٢١ كم^{2}). وبناءً على WRB ، فنجد التتابع الآفقي لأراضي Solonchaks هو A-Btz-C/Bt-Cz حيث يحتوي على أفق ملحي والذي يسبب مُحدات تربة تتعلق بارتفاع محتوى الملوحة (٩.١-٢١.١ ديسيمنز/م). تشير آفقي الصوديوم Natric والملحي Salic في تتابع الآفاق لأراضي Sololnetz Ap-E-Btnz-C إلى مُحدات الصوديوم والملح بنطلق التربة. تشير التسلسل الطبقي لأراضي الأرينوسول (A-Ck-Cq-Cz-Cφ) إلى وجود تربة رملية ملحية عميقة، بينما يشير التسلسل الطبقي لأراضي Leptosol (C-Cφ) إلى وجود تربة رملية ضحلة مع أكثر من ٣٠% من الفتات الصخري. يتطلب كل نوع تربة والتي تم تحديدها بوادي وردان إلى إدارة فريدة تعتمد على السمات السائدة التي تقيد تطور النباتات. فقد اقترحت الدراسة الحالية نهج إدارة تربة مُستدامة لكل نوع تربة. حيث توجد ثلاثة أنواع من الأراضي تحت الدراسة متأثرة بالأملاح بدرجات متفاوتة، فتوجد الأراضي الرملية الملحية Arenosols ذات القوام الخشن والتي تنتهي عند عمق ١٧٢ سم والتي تتركز الأملاح في الطبقات السفلية للقطاع والتي تصل إلى أكثر من ٢٧ ديسيمنز/م في طبقة Cz عند عمق من ١٠٦-١٥٣، والأراضي شديدة التملح خاصة في ٥٠ سم العليا من القطاع ذات القوام متوسط النعومة خاصة بالافق الملحي Btz في أراضي Solonchaks والتي تنتهي عند عمق ١٤٩ سم، والنوع الثالث متمثل في أراضي Sololnetz ذات القوام الناعم وينتهي عند عمق ١٣٨ سم وهو أشد خطراً حيث يجمع ما بين التملح الشديد والقلوية الشديدة في ظل نعومة قوام التربة كما هو بأفق Btnz عند عمق ٥٧-١٠٠ سم. ولكل نوع من هذه الأراضي إدارة معينة لمحاولة إزالة الأملاح من منطقة إنتشار الجذور بالأحتياجات الغسيلية مع إضافة إحتياجات جبسية عند الحاجة كما بأراضي Sololnetz . بالاضافة إلى الأراضي الجيرية Calcareous soils والتي تمتلك أفق كالسي Calcic horizon كما بأراضي Calcisols وتحتاج إدارة مُستدامة للتعامل مع المحتوى الجيري والافق الكالسي، وهناك أيضا أراضي متأثرة بمحتوى عالي من الجير ولا تندرج ضمن Calcisols لعدم وجود بها أفق كالسي مثل أراضي Leptosols و Regosols ، ولكلاً منها إدارة مُختلفة تماماً عن الأخر. توفر الأفكار المستقبلية للتنمية والادارة المُستدامة رؤية شاملة لإدارة الزراعة المُستدامة، وذلك بالتركيز على الإكتمال Completeness والتنوع Diversity والتطور Sophistication والاستدامة Longevity .

كلمات مفتاحية: صولونشاكس,Solonchaks صولونيتز - Sololnetz ليبتوسولس - Leptosols إدارة التربة - Soil management، طيف الاعتمادAdoption spectrum