Impacts of Geomorphic Units on Soil Properties in Wadi El-Ashara, Suez Canal West, Egypt

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ABSTRACT

Soil characteristics and processes are governed by soil formation factors. This study aimed to assess the influence of geomorphological units and related criteria of soil parent material and topographic feature on soil properties and formation in Wadi El-Ashara, Egypt. The impact of bedrock catenas and slope position as geomorphic criteria on soil properties was investigated in Wadi El-Ashara, West of Suez Canal. The obtained results were utilized to investigate variations in the existing diagnostic criteria of the World Reference Base (WRB) and USDA Soil Taxonomy schemes. To reach these objectives, ten soil pedons were characterized across two distinct catenas in Wadi El-Ashara. The study's findings revealed that soil salinity increased downslope on piedmont and basin floor landforms. The summit positions of two catenas have weakly developed soils, but the midslope and downslope positions have more developed soils because the stable topography permits the formation of gypsic, calcic, sodic, and salic horizons. By the USDA system, soils of limestone catena were classified as *Lithic Torripsamments* and *Lithic Torriorthents* at the upslope positions, *Sodic Haplocalcids* at the midslope position, and *Typic Torriorthents* and *Typic Haplocalcids* at downslope position. The soils at the toeslope of the limestone catena were grouped as *Solonchaks by the WRB* system, since the salinity fits the requirements of salic horizon in the WRB system, but did not fit according to the USDA system, which should be standardized. This feature strongly influences soil classification and soil types across the studied two catenas. Furthermore, the soils of uppermost areas of gypsum catena (summit and shoulder) were classified as *Lithic Torriorthents* and *Leptic Haplogypsids* according to USDA system instead of *Leptosols* and *Gypsisols* by the WRB system while soils in the backslope and footslope, with secondary gypsum accumulations, were categorized as *Typic Haplogypsids* by USDA system and *Gypsisols* by WRB system. Topography across slope positions induced differences in soil depth, soil texture, water retention, soil salinity, horizonation, and morphology of studied soils from the summit to the toeslope along both catenas. According to the study's conclusions, the current versions of the WRB and USDA systems have shortcomings that necessitate standardization in order to improve these systems and develop a uniform classification method. Parent material and topography across distinct slope positions were identified as the two primary soil-forming factors influencing soil properties in the two examined catenas at Wadi El-Ashara.

Keywords: Catena, Gypsum, Lime, Soil formation, Soil Characteristics, Soil Taxonomy.

INTRODUCTION

Geomorphology aids in better understanding of soil formation. Soil data from various landscape sites can also be used to understand geomorphological processes (Meier *et al.,* 2023). Geomorphology is a natural geography science dealing with the topography of the Earth (Garajeh *et al.,* 2022). The primary purpose of geomorphology is to define topographic formations and their properties through quantitative analysis (Kasprzak *et al.,* 2019). The physiological and morphological aspects of the Earth that characterize its historical and present active processes are referred to as topography (Li *et al.,* 2020). Quantitative geomorphology is a branch of geology that detects and categorizes the landforms that shape the Earth's surface and provide numerical data (Mohamed *et al.,* 2018). In arid soils, geomorphological position influences solum depth through salt leaching and weathering rate (Li *et al.,* 2020). The link between soil and relief has been investigated using pedology and geomorphology (Roudier *et al.*, 2022).

Desert areas cover more than 30% of the Earth's surface and can be found on nearly every continent (Garajeh *et al.,* 2022). They are vulnerable environments and even small disruptions can result in large changes to the landscape. Deserts usually have a small number of settlements. However, it is also often the site of economic activity such as solar energy and oil exploration. Different topographic units characterize arid environments and give rise to unique landscapes (Leizica *et al.,* 2022). Some desert terrains are mobile and cannot be classified as either eroded or sedimentary (Roudier *et al.,* 2022). It is also a fast evolutionary process and easy to study compared to most rock erosion forms. Field-based techniques (such as the Global Positioning System "GPS") are the predominant method of identifying and mapping desert terrain (Leizica *et al.,* 2022). Its measurements are limited to

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regions and specific months and seasons. Furthermore, many of the world's deserts are remote, harsh, and terrestrial, making traditional methods of mapping and monitoring these areas exclusive and difficult (Ma *et al.,* 2019).

The parent material and geomorphologic processes have been identified as the primary soil-forming factors in desert ecosystems around the world (Frank Buss *et al.,* 2020). Soils across a slope transect may develop in an interdependent manner under the same parent materials. A soil catena is a group of linking soils that characterize and form under different slope positions. In arid and semi-arid areas, slope-dependent pedogenic processes are critical for enhancing the variety of vegetation or soil cover (Leizica *et al.,* 2022). Relief, climate, parent material, organisms, and soil formation time are soil-forming factors (Jenny, 1980). The aforementioned factors impact soil-forming processes and soil characteristics. Parent material influences soil-water permeability in the early phases of pedogenesis and thus it governs the speeds of formation processes (Bateman *et al.,* 2019). Several soil characteristics are influenced by geomorphic position and relief-controlled microclimate across environmental gradients of the landscape (Roudier *et al.,* 2022). Organisms have potential effects on soil weathering rates and differing soil types for soil formation and development. People are frequently regarded as organisms that influence soil pedogeneis through human intervention in land utilization types selection and farm management (Yang *et al.,* 2020).

Erosion as a geomorphic process in semiarid mountainous may overprint lithological signatures and climate compared to humid environments (Mukherjee *et al.,* 2020). Major soil types in desert lands were differentiated based on parent materials and pedogenic processes, i.e, calcification, gypsification and salinization vertically across soil profile horizons (Bateman *et al.,* 2019 and Delbecque *et al.,* 2022). Arid-regional soil surveys have produced a wealth of knowledge and information about new soil types, resulting in ongoing revisions to existing classification schemes and systems (Pindral *et al.,* 2020). Calcareous, gypseous, and saline soil classification has been extensively studied utilizing both the USDA Soil Taxonomy and the World Reference Base (WRB) for Soil Resources. These systems aim to provide consistent criteria and standards for recognizing diagnostic horizon characteristics and locating soil types (Frank Buss *et al.,* 2020). These frameworks may be combined into the Universal Soil Classification System (USCS) as a global system by the International Union of Soil Sciences (IUSS) (Yang *et al.,* 2020). This USCS will enable investigators from diverse scientific areas to distinguish different types of soil consistently and rapidly, hence improving soil science as a whole (Camacho *et al.,* 2020). To distinguish soils based on their eco-functions, some writers believe that soil taxonomies should choose features connected with ecologically relevant factors (Roudier *et al.,* 2022).

The current work aimed at (1) identifying pedomorphological, physicochemical properties, and chemical characteristics of Wadi El-Ashara soils, west of Suez Canal related to geomorphic positions; (2) investigating the effects of geomorphic units across slope positions on two different parent material catenas development and soil diversity in the study area, and (3) characterizing soil classification using both WRB (2022) and USDA Soil Taxonomy of Soil Survey Staff (2022) with assessing observations to improve their coherence and development of the USCS for accurate soil classification.

MATERIALS AND METHODS

Study area selection and description

Wadi El-ashara is situated near the cities of Fayed and Abou-Sultan, Ismailia Governorate, Egypt along the Suez Canal and Great Bitter Lake (Fig. 1). Selected soils were sampled within two different catenas covering an area of 1000 km^2. These catenas of Wadi El-Ashara have a high level of biodiversity for a desert ecosystem. Soils across these catenas have never been studied, despite their recognised ecological value. Wadi El-Ashara lies in northeast Egypt, near the southwestern end of the Suez Canal Development Corridor. Latitudes 29° 50' N and 30° 24' N, and longitudes 31° 50' E and 32° 17' E, define the area (Fig. 1). It is covered with sediments and sedimentary rocks dating from the middle Miocene to the Quaternary periods. The El Shatt formation is exposed to the east of the Bitter Lakes and represents the middle and late Miocene. Limestone, sandstone, gypsum, and mudstone are all found in this formation (Abdeen *et al.,* 2018). The Hagul formation represents the late Miocene and formed of non-marine deposits such as sandstone, limestone, gravel, and flint pebbles. Quaternary sediments comprise a considerable portion of the midslope and downslope postion of study area. These sediments are mainly consisted of gravel, sand, clay, salt marshes, and Wadi deposits. The study area has been characterized by tectonic activity from the Oligocene period. The basic topography disparity between the coastal plains in the east and the high fault block of the Gebel Ataqa in the south is due to the tectonic activity (Abdeen *et al.,* 2018). The Gebel has been surrounded by faults since at least the Pleistocene (Said, 1962). It is a dissected plateau characterized by Eocene limestones from the middle and upper Eocene epochs. Wadis that rise on the Gebel disgorge water and sediment onto the coastal plains, dominating their geomorphological character as the principal supply of sediment (Bush *et al.,* 1980). The geomorphology of the study area is dominated by alluvial fans, piedmont slopes, the mountain front, bedrock surfaces, and the limestone plateau of Gebel Ataqa, as well as the coastal fringe of emergent marine features (Said, 1962).

The Wadi El-Ashara study region has an arid environment, with an annual precipitation of about 13 mm and an average annual temperature of 33°C. Wind patterns help to increase the yearly average reference evapotranspiration to roughly 105 mm. Given all of this, this region has one of Egypt's biggest water deficits (Egyptian Meteorological Authority, 2022). Based on the standard measures of Soil Survey Staff (2022), the average annual soil temperature of study area is 21°C. At a lithic contact or at a depth of 50 cm vertically within the soil studied pedons, the difference in mean summer and mean winter soil temperatures is 9°C. As a result, the soil moisture and temperature regimes were assumed to be *aridic* and *thermic*, respectively (Soil Survey Staff, 2022).

Field study and sampling

Ten soil pedons were distributed on two curved transects across two separate catenas namely limestone catena (610 km^2) and gypsum catena (390 km^2). Five pedons were chosen for each catena at different slopes up to 35%. Representative pedons were described at different slope points along the two transects across the studied catenas (Fig. 2 & Table 1). The geomorphic sites are referred to as the upslope (summit and shoulder), midslope (backslope), and downslope (footslope and toeslope) (Fig. 3). Horizon designation suffixes were applied using USDA Soil Taxonomy of Soil Survey Staff (2022). Sampled soils were collected from methodologies given by FAO (2006) genetic horizons of soil pedons in the studied catenas. Pedomorphological descriptions of each horizon/layer of the representative pedons and their sites were carried out in the field using the standard terms of Schoeneberger *et al.* (2012). The soil criterion limits were interpreted using the soil survey guidebook of Soil Science Division Staff (2017). Soil moist colors were quantified using the Munsell Color (2009).

Landscapes of Wadi El-Ashara

The research area's site at Wadi El-Ashara featured a variety of significant landscapes and landforms across an elevation gradient spanning from 45 to 405 meters for limestone catena and from 90 to 305 meters above sea level for gypsum catena (Table 1). Different geomorphic units and landforms were defined using GIS package (ArcScene) with the aide of the Landsat satellite images and digital elevation model (DEM) as shown in Fig. (3). Landsat-8 scene of study area with 30 m spatial resolution was acquired in 2020. Digital elevation model (DEM) was generated based on topographic maps and contour lines digitizing within ArcGIS 10.1 package. The geomorphic map of study area was imported to ArcGIS and then georeferenced to extract different geomorphic units and landforms across slope positions of Wadi El-Ashara study area. The study area has been classified into three major landscapes from downslope to upslope: basin floor, piedmont, and mountain landforms (Fig. 4 & Table 1). As shown in Table (1), these landscapes were split into geomorphic components and distinct landforms using the standard taxonomic logic and terms given by Peterson (1981), Wysocki *et al.* (2000) and Soil Science Division Staff (2017). However, anthropogenic activities have caused local changes to the natural downslope landforms. Hillslope position (i.e., slope position) was chosen as a two-dimensional descriptor of parts of line segments along two transects that run up and down the slope of two catenas, e.g., summit and shoulder at upslope, backslope at midslope as well as footslope and toeslope at downslope, as illustrated in Fig. (3).

Analytical methods

Soil horizons of investigated pedons were described, including moist color, texture, consistency, pedogenic, and redoximorphic features. Undisturbed and disturbed soil samples were obtained from each soil horizon or layers of investigated pedons across the two catenas. At room temperature, disturbed soil samples were air-dried and separated from the coarse earth fractions (gravel, cobbles, and stones). Soils were taken from two catenas and processed for physical and chemical laboratory investigation. The gravel and coarse particles content was determined (Soil Survey Staff, 2014). Soil texture and fine earth fractions (sand, silt, and clay) were measured using dry sieving and the pipette method (Pansu and Gautheyrou, 2006). Water holding capacity (WHC) is calculated using the field capacity and wilting point measurements (Richards, 1947). A volumetric pressure plate extractor was used to quantify them. Using gravel corrections (Soil Survey Staff, 2014) and bulk density (Grossman and Reinsch, 2002), one value of water holding capacity (mm) for each pedon was computed using the equation proposed by Badía *et al.* (2013):

$$\mathbf{WHC} = \sum_{i=1}^{i} [(\mathbf{FC} - \mathbf{PWP})_i \times (1 - \mathbf{G})_i \times (\mathbf{Bd}_i) \times (\mathbf{T}_i)]$$

Where WHC stands for water holding capacity (mm) per soil pedon, FC stands for field capacity, PWP stands for permanent wilting point, G stands for gravel, Bd stands for bulk density, T stands for soil horizon thickness (metres), and i stands for horizon relative to 150 cm depth or lithic contact.

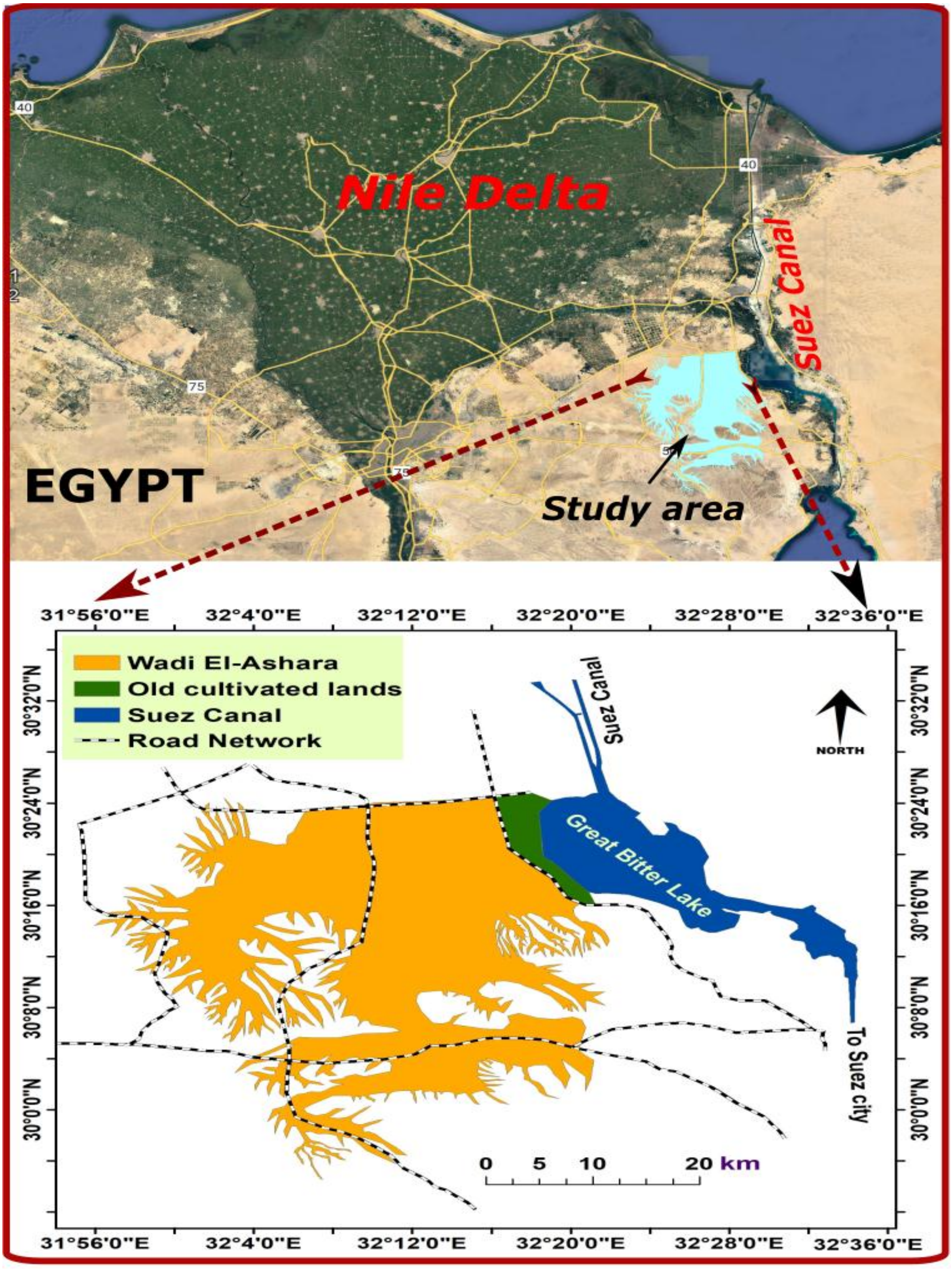

Fig. 1. Location of Wadi El-Ashara study area, West of Suez Canal, Egypt

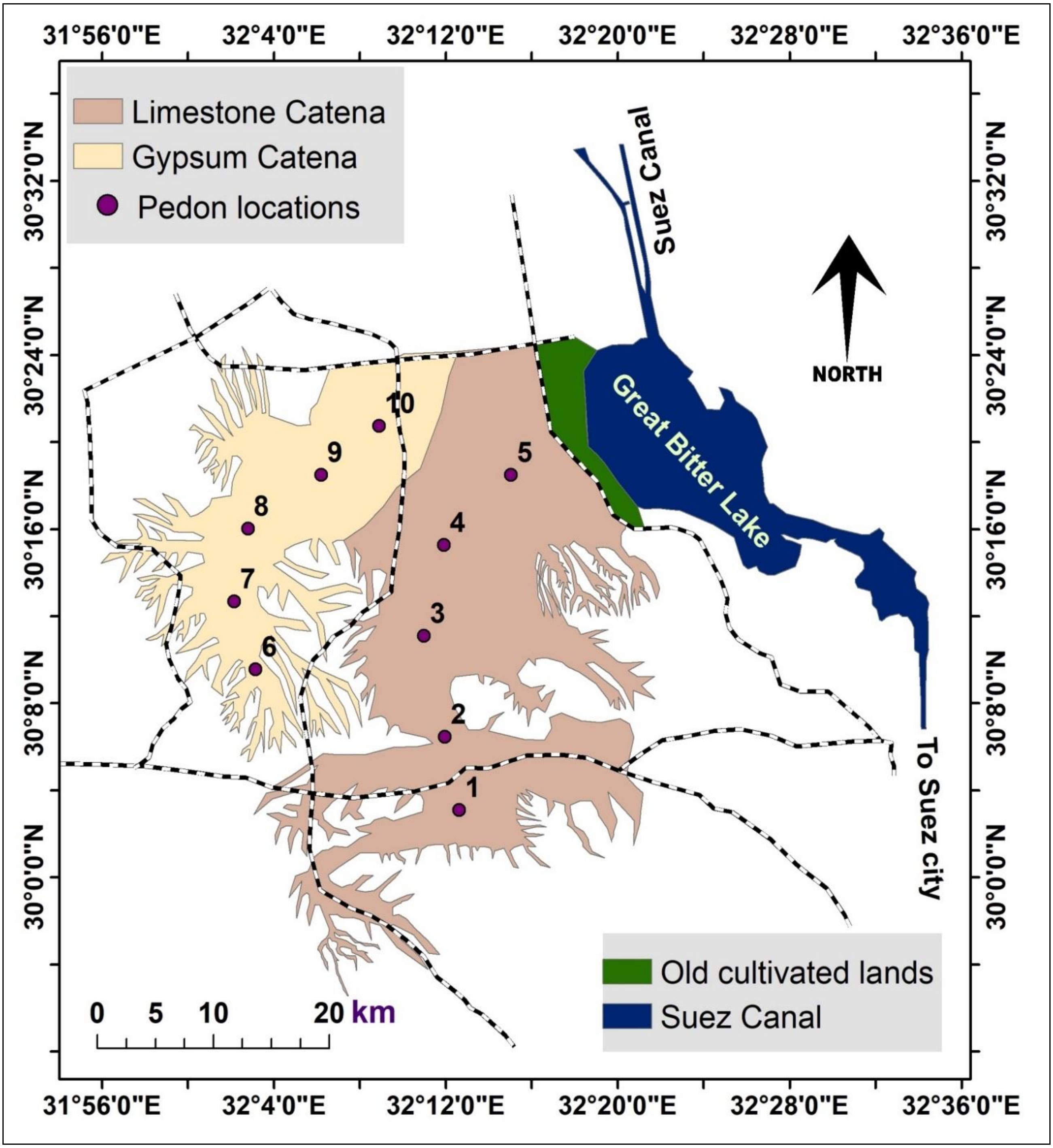

Fig. 2. Pedon locations across the two catenas of Wadi El-Ashara

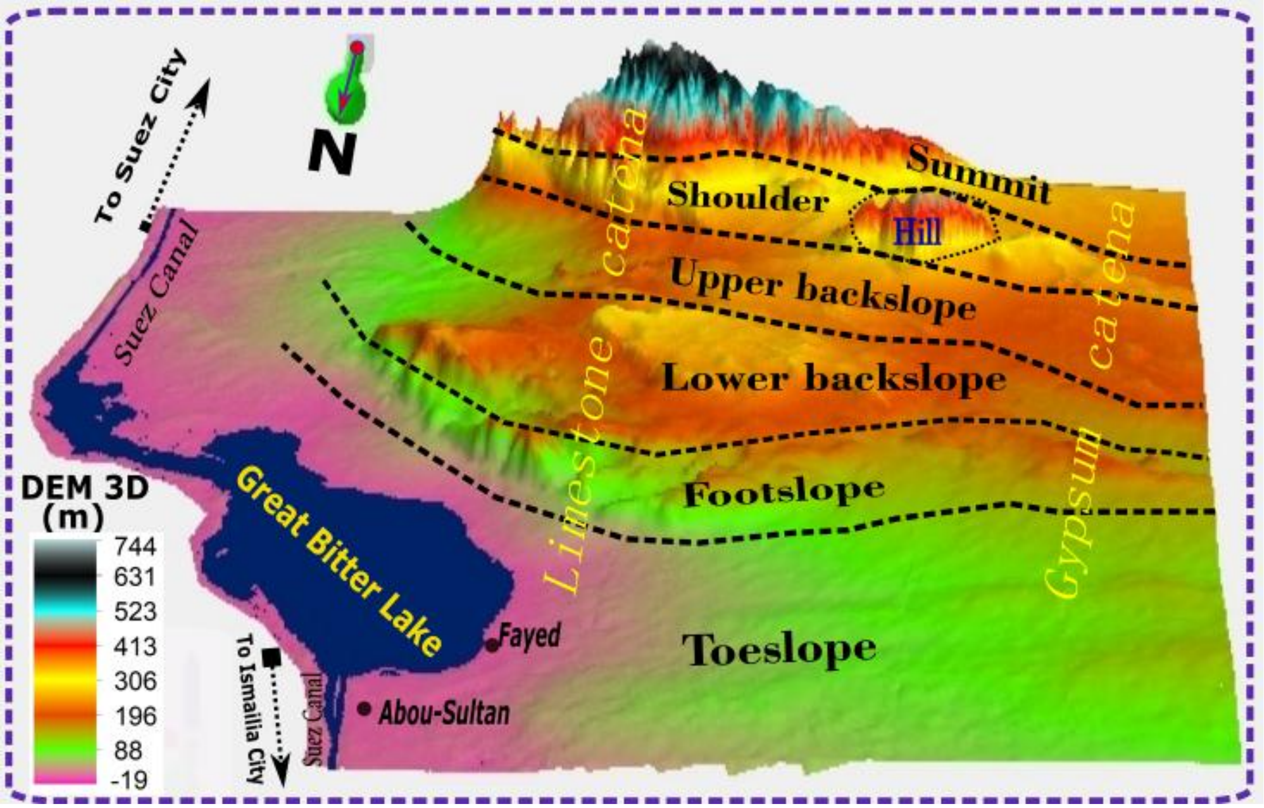

Fig. 3. DEM 3D visualization showing slope positions of Wadi El-Ashara study area

After treatment with 6 N HCl, a calcimeter instrument was used to determined total carbonate content as $CaCO_3$ (Nelson, 1982). Thermogravimetric method was used to determine soil gypsum content based on the loss of gypsum crystal water after heating to 150°C when gypsum is converted to anhydrite (Nelson *et al.*, 1978). Total soil organic carbon (SOC) was determined using the wet oxidation method (Nelson and Sommers, 1982). The electrical conductivity (EC_e) of saturated soil paste at 25°C was used to determine soil salinity (Rhoades, 1982). Soil Survey Staff (2014) standard procedures were used to measure and quantify exchangeable sodium percentage (ESP). The USDA Soil Taxonomy System (Soil Survey Staff, 2022) and the World Reference Base for Soil Resources as reported by the International Union of Soil Science (WRB, 2022) were used to classify soils of the Wadi El-Ashara study area.

RESULTS AND DISCUSSION

Geomorphological Characteristics

Landform units and their boundaries were recognized during soil survey with the aide of Landsat satellite imageries. DEM, slope positions, landforms, and geomorphic processes and their interactions on soils in the study area are illustrated in Figs. (3, 4, 5, 6 & 7). Table (1) lists the salient site description and geomorphic positions across the sampled catenas in study area. Furthermore, the landforms were divided within the mountains classification following (Wysocki *et al.*, 2000) and (Hirmas and Graham, 2011). Mountainbase landforms are found near the base of mountain slopes and are primarily composed of thick colluvium wedges. Mountainflanks are long, intricate mountain sideslopes covered with colluvium and residuum-derived desert pavements (Hirmas *et al.*, 2011) that are found locally across the research area (Fig. 7). This study site's mountainflank has internal components such as hills, colluvial aprons, and pediments (Fig. 7). Mountainflats are wide, open plains with low-relief terrain within the mountain range (Figs. 4 & 7). Mountaintops are defined in this study as crest of a mountain (Fig. 4). At upslope positions of study area, desert pavement was observed on numerous landforms of the mountain. Desert pavement is a unique characteristic of desert landscape made up of closely packed clasts with bottoms. It is most common on mountaintops and free faces, with only a few exceptions on mountainflanks and mountainbases (Hirmas *et al.*, 2011) (Fig. 7).

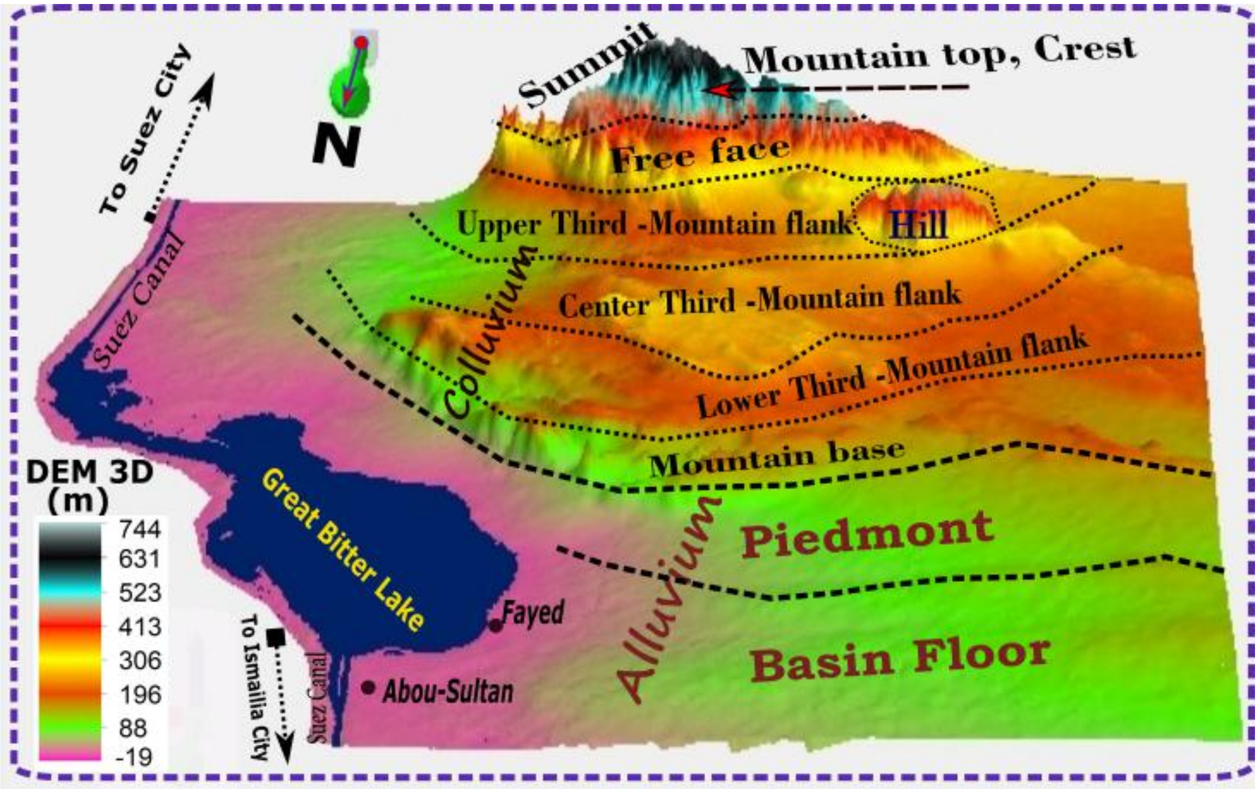

Fig. 4. Landforms across a slope gradient in Wadi El-Ashara study area

Table 1. Certain geomorphic characteristics across the sampled catenas in Wadi El-Ashara study area

Soil catena	Sampled pedons	Total depth, cm	Surface morphometry				
			Slope position	**Landscape**	**Geomorphic component / landform**	**Slope gradient[1]**	**Altitude range(m); MTL [2]**
Limestone Catena	P1	35	Summit	Mountains	Mountain top	07	405-330
	P2	45	Shoulder	Mountains	Free face	06	330-275
	P3	90	Backslope	Mountains	Mountain base	05	275-210
	P4	130	Footslope	Piedmont	Fan piedmont	03	210-135
	P5	155	Toeslope	Alluvial plain	Alluvial Plain	02	135-45
Gypsum Catena	P6	40	Summit	Mountains	Upper Mountain flank	05	305-275
	P7	60	Shoulder	Mountains	Lower Mountain flank	04	275-180
	P8	85	Backslope	Mountains	Mountain base	03	180-145
	P9	110	Footslope	Piedmont	Fan piedmont	03	145-110
	10	150	Toeslope	Basin floor	Alluvial Plain	02	110-90

All abbreviated parameters are listed in this table following FAO (2006) and Schoeneberger *et al.* (2012); (1) 02: level, 03: nearly level, 04: very gently sloping, 05: gently sloping, 06: sloping, 07: strongly sloping; (2) MTL: mean tide level reported in meter, formerly mean sea level (MSL).

Lacustrine sediments at the east of study area were observed on the basin floor's downslope. The lake system's cyclic water level variations resulted in evaporates lithofacies and alternating carbonate indicating low and high water levels, respectively (Camacho *et al.*, 2020). With no signs of considerable deformation, carbonate deposits cover evaporate deposits. The lithofacies of the upslope positions are dominated by carbonate and gypsum. The evaporite lithofacies make up the foothills at the midslope's lowest regions (Hirmas *et al*., 2011).

Soil-geomorphic Relationships

The linkages among parent material, topography, and soil as the main components of soil-geomorphic pattern are shown in Fig. (5) as illustrated by Monger and Bestelmeyer (2006). Soil is the chemical, biological, and physical medium through which ecosystems interact and connect with one another (Kasprzak *et al.,* 2019). In this sense, geomorphic refers to both the geologic composition of soil parent material and the slope positions (Camacho *et al.*, 2020). The lithic legacy is especially visible in the arid climate of Wadi El-Ashara. The nature and distribution of geomorphic processes which take place in the studied area are illustrated in Fig. (6). Erosion-sedimentation processes relate soil formation to parent material because soil eroded from upslope areas generates sediment and soil parent material in downslope landforms from which a new soil originates (Fig. 6). The three-dimensional configuration of a landscape, known as topography, is intimately linked to soil development via erosion and sedimentation (Fig. 6). Time as a soil formation factor influences soil erosion and the resulting sedimentation (geologic processes) in the development of soil types with different depths and various horizons of soil pedons across different slope position of the two catenas of Wadi El-Ashara.

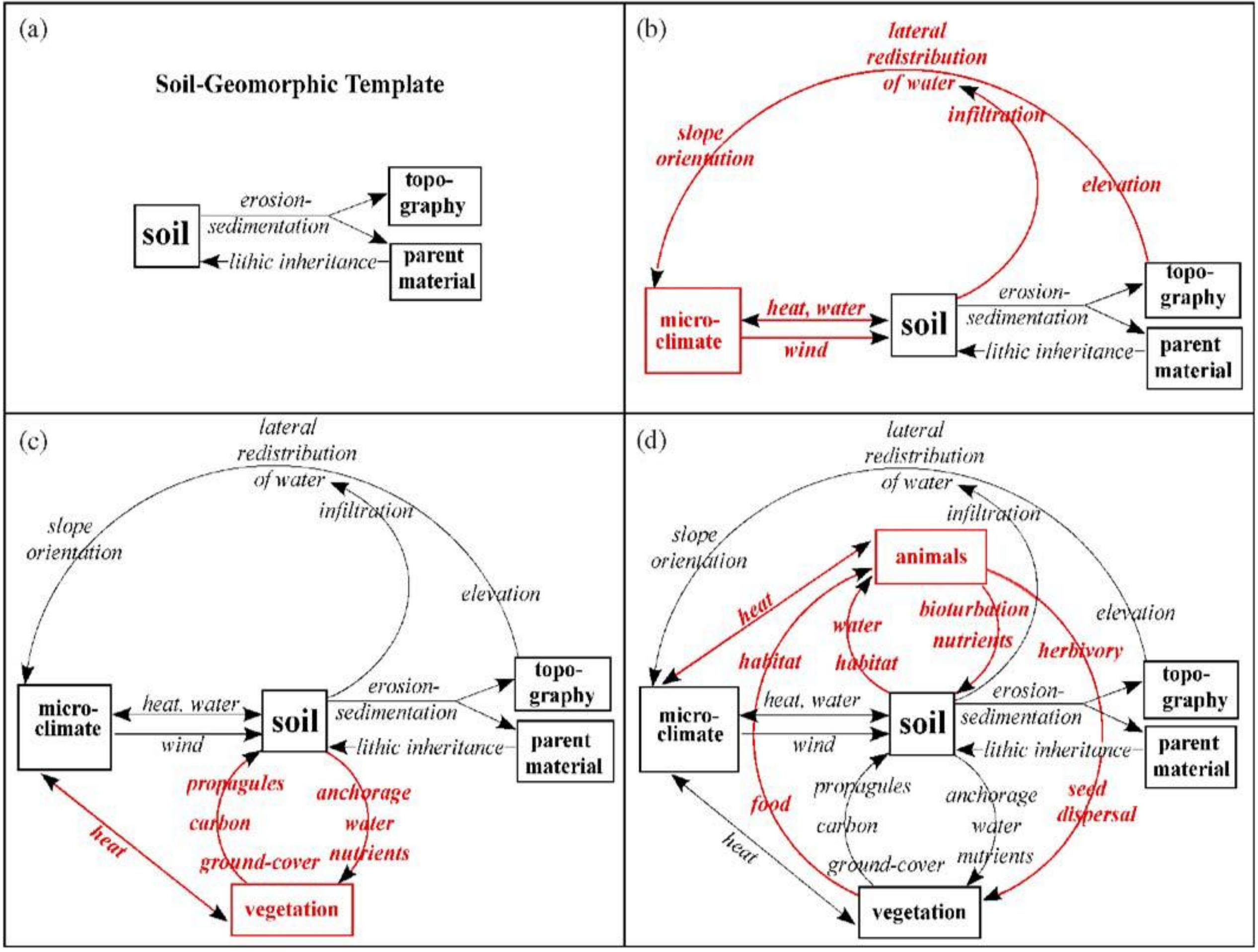

Fig. 5. Design for soil-geomorphic relationships. (a) Main of the soil-geomorphic pattern components (topography, parent material, and soil). The red linkages indicate the relations among soil, microclimate(b), vegetation(c), and animals(d) (Monger and Bestelmeyer, 2006)

The microclimate is the climate near the ground, i.e. from the soil surface to the plant canopy height (Casalini and Bisigato, 2017). Microclimate fluctuates as a function of local topography within a regional climate with temperature and moisture regimes (Camacho *et al.*, 2020). Elevation, lateral water redistribution, and aspect are the elements of local topography in the research area of Wadi El-Ashara that influence microclimate (Fig. 7). Wind has an effect on soil by accelerating erosion, particularly on exposed sandy soil in upslope positions (summit and shoulder in both catenas). Water runoff is also an important erosion agent at downslope positions (footslope and toeslope).

The slope aspect in the research area's upland mountains has a significant impact on the vegetation patterns and diversity of soil qualities in the lowland at the basin floor of Wadi El-Ashara. The soil in the research area of Wadi El-ashara is influenced by vegetation via different key linkages: plant-available water, soil organic carbon, roots anchoring, vegetative ground cover, and critical nutrients (Fig. 5). Vegetation and animal activity influences geomorphic change and increases the solum depth to bedrock. Bare desert land cover and erosion process increase as ground cover declines and vice versa (Ríos *et al.*, 2018). The rise in carbon concentration caused by all living species' transpiration and desertification processes may affect CO_2 levels in the atmosphere, causing climate change (Lopes *et al.*, 2022). However, photosynthesis by vegetation can reduce CO_2 levels in the atmosphere (Fig. 5).

To better understand the soil-geomorphic interactions, Fig. (7) displays the proposed theoretical model of the key geomorphic processes in the investigated area, as hypothesized in the current study after Hirmas *et al*. (2011). Dust is carried by the wind from upland landforms and deposited on downslope land forms across slope positions of Wadi El-Ashara. Furthermore, dust, alluvium, and mass movement processes were swept away by flash flooding and rain within upland mountain rock fragments to downland (Hirmas and Graham, 2011). This downward water increases bedrock weathering and, as a result, soil development (Camacho *et al.*, 2020). As a result, the mountains of upland are a source of alluvium and a significant sink for dust, whereas the basin floor of downslope is a potential sink for alluvial deposits and a source of eolian sediment (Hirmas *et al*., 2011) (Fig. 7).

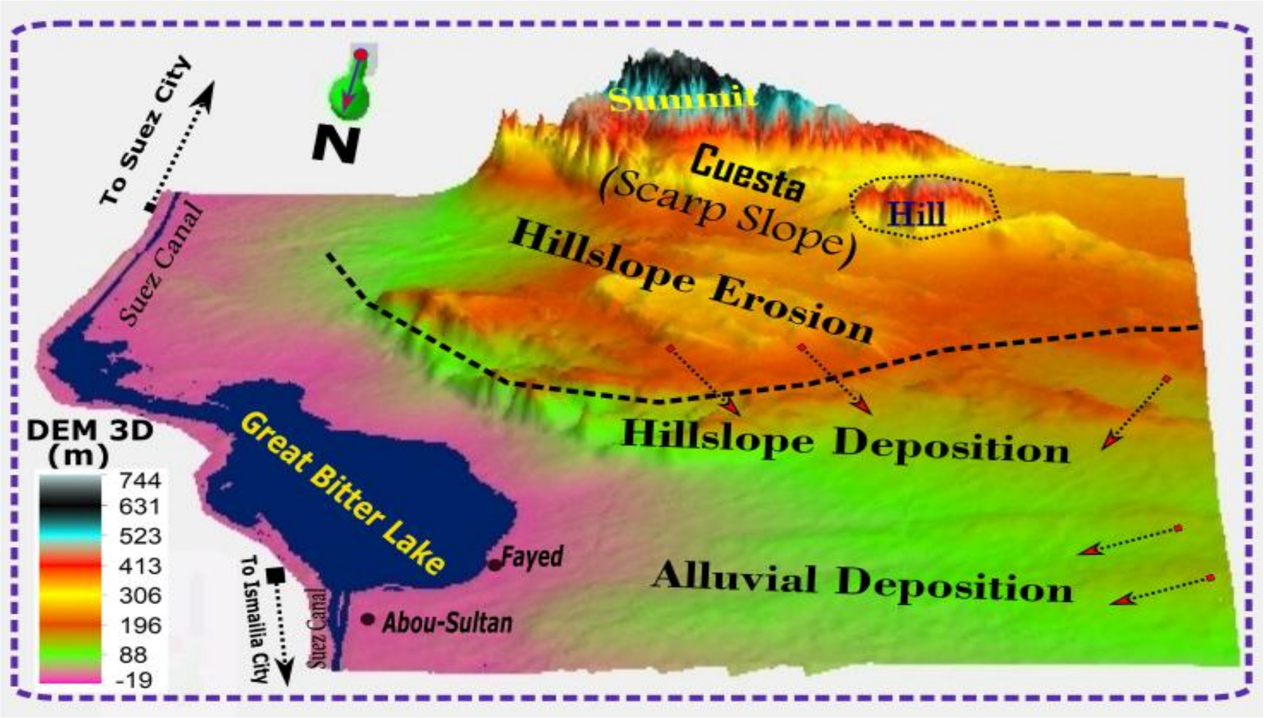

Fig. 6. Geomorphic processes occurred within two catenas of Wadi El-Ashara

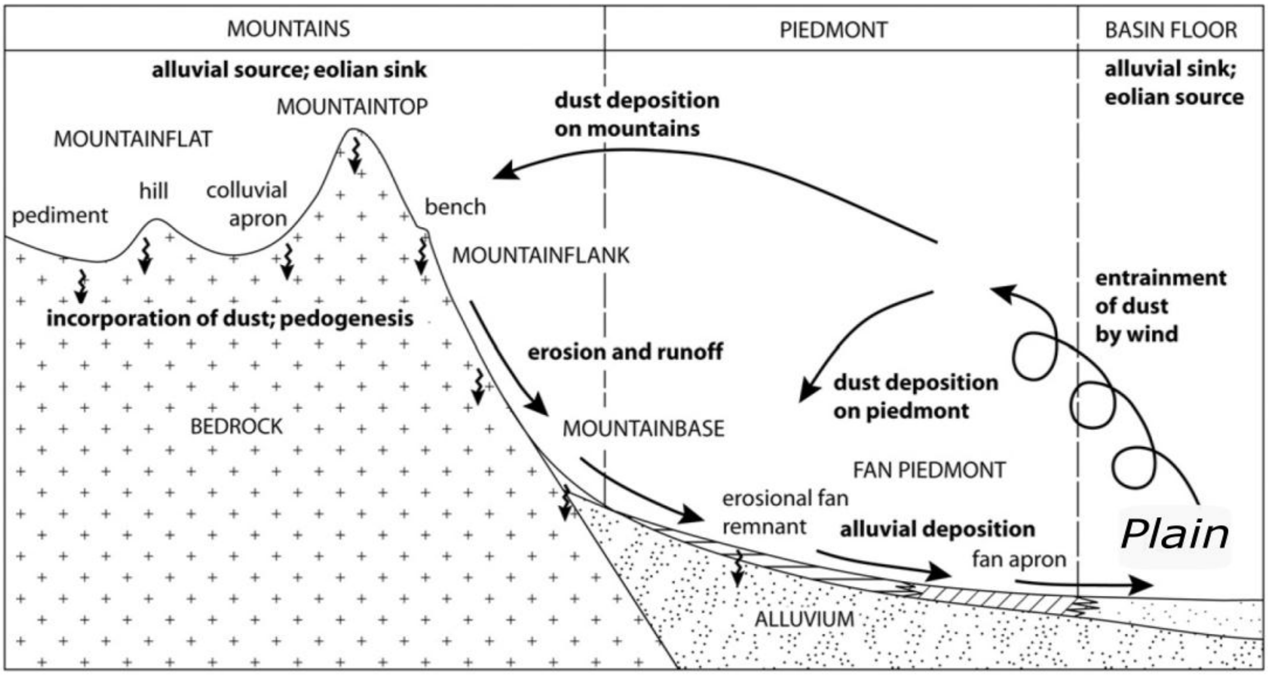

Fig. 7. A geomorphic model showing the interactions among mountain, piedmont, and basin floor to form soil at different slope positions (modified after Hirmas *et al*., 2011).

In conclusion, this study reveals that land surface characteristics have an important role in soil-geomorphic processes in the arid gypsum and limestone catenas of Wadi El-Ashara. The arid mountains of the research region are extremely good at capturing and storing dust due to the combination of high surface roughness on upland positions and the stabilizing impact of surface desert pavement on downslope positions. Wind can transport soluble salts and fine-grained dust back into the mountains at the landscape scale, whereas water delivers sediments to lowland depositional landforms as shown in Fig. (7). The uplands serve as long-term storage sites because a major amount of these eolian deposits are washed between rocks and absorbed into the soil (Figs. 6 & 7).

Soil Characterization

Tables (2, 3, 4, & 5) summarized the pedomorphological and physicochemical features of soils in the two examined Wadi El-Ashara catenas. Even though all the texture of most soil pedons was sand to silt loams, increase in clay content with depth was noted especially in the pedon of downslope positions (Tables 2 & 3). The toeslope pedons had more abundant RMF and more abundant roots, than the upslope pedons (Tables 2 & 3). The high abundance of RMF is due to a decrease in soil permeability and a significant decrease in clay content within the horizons of studied soil pedons. The roots abundance in the surface layers of studied pedons at downslope soils is due to the vegetation cover. The activity of roots and microorganisms may increase organization of soil beds and decrease hardness of soil consistence (Tables 2 & 3).

Nonetheless, considering that loess is a huge material in general, the above-mentioned vertical tendencies were most visible in the downslope pedons. In gypsum and limestone catenas, the toeslope pedons had five and six soil horizons or layers, respectively (Table 2 & Figs. 8 & 9). The Ap horizon in the downslope pedons was generated by ploughing and human manipulation of the soil through farming activities. All examined soils had pH levels ranging from 7.35 (slightly alkaline) to 9.05 (very strongly alkaline). For both catenas, the highest ESP values were found in downslope positions (Tables 4 & 5).

The colluvium sediments at the summit (P1) and shoulder (P2) of the limestone catena have C-Cr layer sequences and A-C horizon sequences, respectively, whereas the alluvial soils at the piedmont and basin floor have A-Bk1-Bk2-Cr for P3, Ap-2Bd-3Bk-4C1-4C2 for P4, and Ap-Bw-Btkm-Btkz-Bkm-2C for P5 as shown in Fig. (8).

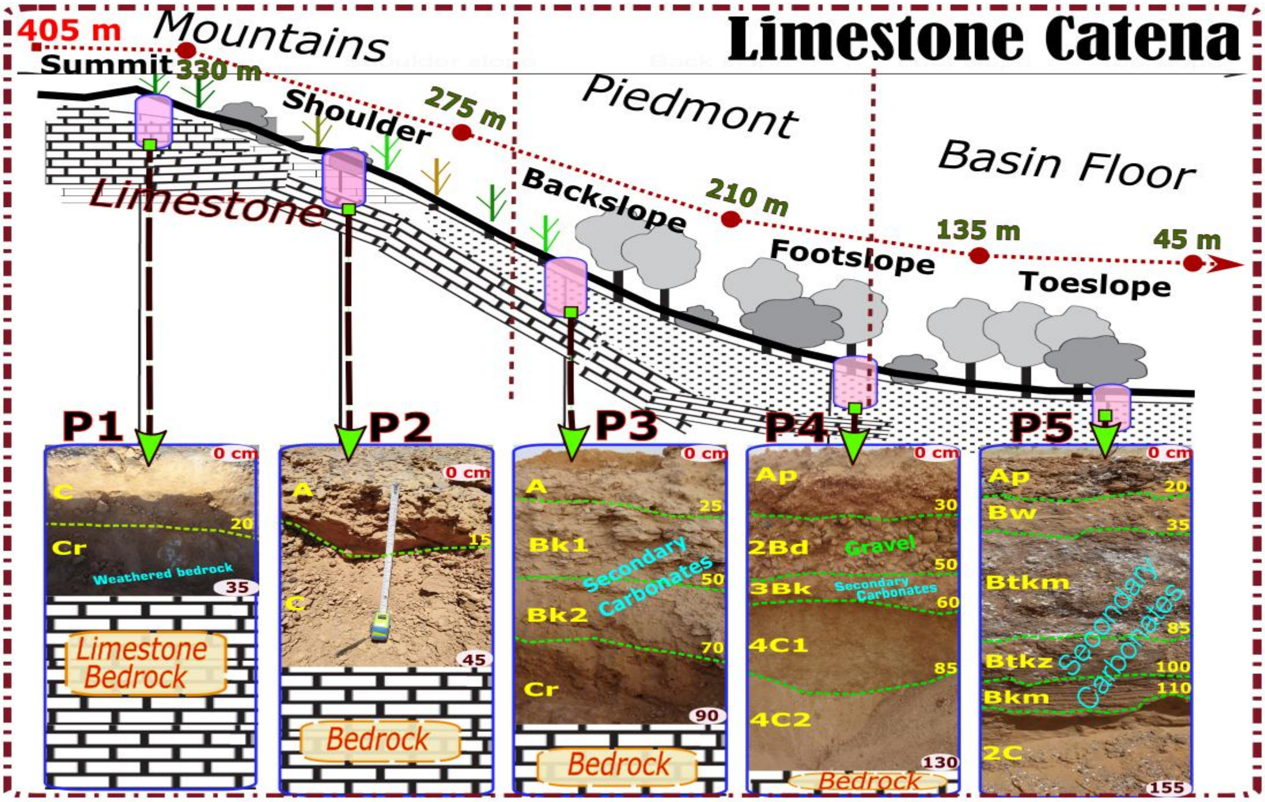

Fig. 8. Soil pedons from a transect across limestone catena of Wadi El-Ashara study area

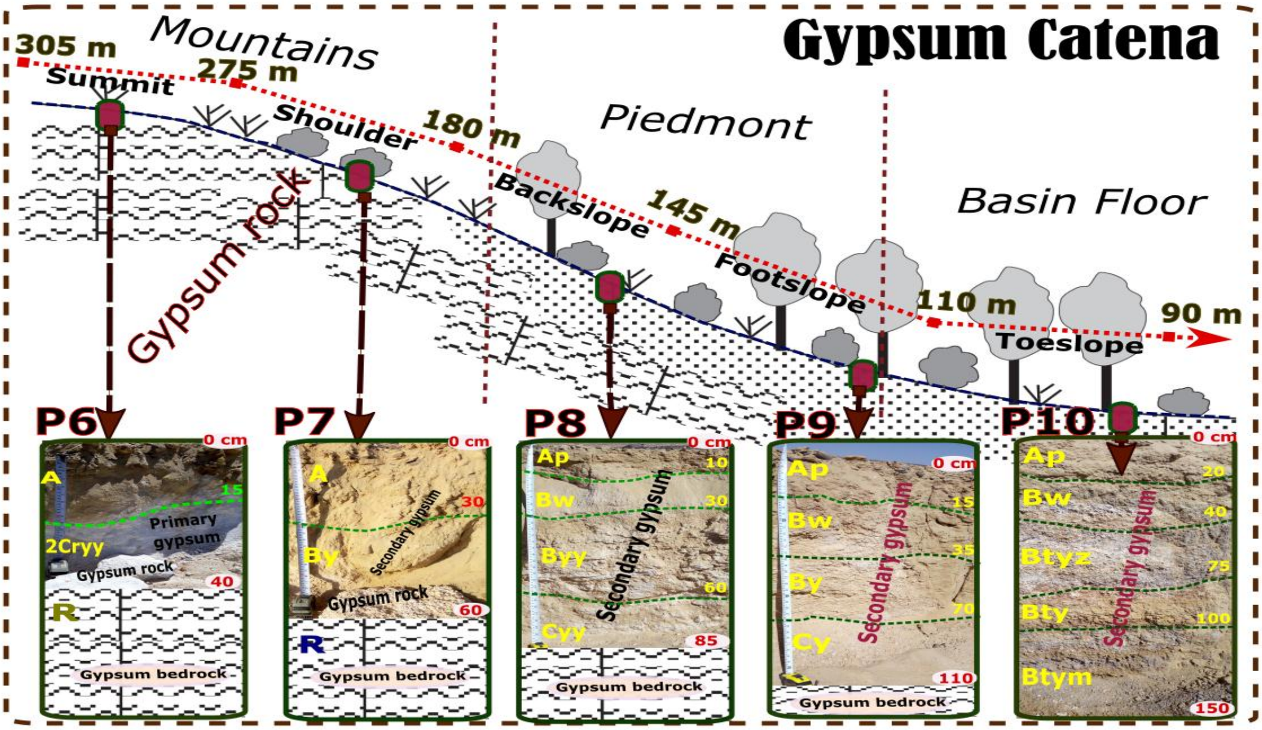

Fig. 9. Soil pedons from a transect on gypsum catena of Wadi El-Ashara study area

Across transect on limestone catena, surface horizons of studied pedons have colors ranges from very pale brown (10YR 8/3) for layer (0-15 cm) in the P2 at shoulder to dark reddish brown (7.5YR 3/2) for epipedon (0-20 cm) in the P5 at toeslope position (Table 2). The soils that is dark in moist color were observed in downslope of limestone catena while soils in the gypsum catena were lighter in color such as white (7.5 YR 8/1) at subsurface layer of P6 at summit. The soils of P5 at toeslope of limestone catena comprised surface horizon with moderate very fine granular structure that transitioned into a subangular blocky structure vertically within the soil pedon (Table 2& Fig. 8). Soils of P6 at summit of gypsum catena were structureless, transitioning to granular and suangular blocky structures in the soils of P10 at downslope position (Table 3). The subsurface layers (2Cryy of P6, Cyy of P8 & Cy of P9) of the gypseous soils were also structureless moving to angular blocky structure in the Btym horizon of P10 at toeslope (Table 3& Fig. 9). However, Tables (2 & 3) describe in detail the consistence, pedogenic features, redoximorphic features, and vegetation roots of both examined catenas.

The Ap horizons of P3, P4, and P5 on limestone catena had higher contents of total SOC (0.51-1.05%) than the Ap horizons of P8, P9, and P10 on gypsum catena (0.41-0.95%) (Tables 4 & 5; Figs. 8 & 9). Calcareous soils have higher biomass plant cover and organic carbon incorporation than gypseous soils due to their higher elevation and improved fertility (Badía *et al.,* 2013). The SOC content of both analyzed catenas was highest at the toeslope positions, followed by the footslope, backslope, shoulder and summit. SOC may be reduced in upper and midslope positions at summit and shoulder due to increased erosion and colluviation processes, respectively. The limestone catena's soils have high $CaCO_3$ content (2.35-35.65%) due to inheritance from the underlying parent material and calcification processes (Table 4). Similarly, due to inheritance from the underlying gypsum material and gypsification processes, the gypsum catena's soils contain significant gypsum contents (3.05-63.51%) as shown in Table (5). Secondary $CaCO_3$ are seen as carbonate masses and nodules as pedogenic structures in toeslope and footslope soils (Table 2). According to the nature of bedrock and non-leaching environment, the gypsum concentration in subsurface horizons of P8 (Byy & Cry) on gypsum catena is extraordinarily high (54.11-63.51%), as indicated in Table (3) and Fig. (9).

Soluble salts (EC_e) are slightly low in limestone catena soils at the summit and shoulder, where it ranges from 0.21-0.36 dS m^{-1}, but grow downslope at the toeslope, where it reaches 31.05 in the Btkz horizon (85-100 cm) of P5 (Table 4). Furthermore, in the toeslope of gypsum catena the Btyz horizon (40-75 cm) of P10 had the highest soluble salts accumulation (>16 dS m1) (Table 5). This could be attributed to saline groundwater seepage and leaching from upslope landforms.

Pedogenetic Considerations

Tables (2 & 3) show the pedogenic features and related pedomorphological characteristics of the two examined catenas of Wadi El-Ashara. Colluviation and bioturbation are geologic processes that influence the soils in both catenas, though to varied degrees depending on biomass output and slope steepness (Fig. 7). The defining pedogenic processes, however, are calcification, which occurs occasionally on limestone catena, and gypsification, which occurs in gypsum catena to form different types of soils (Fig. 8,9). For implementing soil classification, diagnostic properties, diagnostic materials, and diagnostic horizons were determined through soil characteristics. As a result, soil classification and soil type identification were performed using the WRB (2022) and USDA Soil Taxonomy of Soil Survey Staff (2022) classification methods, as stated below. In the soils examined, the following diagnostic surface and subsurface horizons were detected.

Ochric epipedon

An ochric epipedon (Ap) was observed in soil pedons occurring on footslope and toeslope positions of limestone catena with 20-30 cm thick. Also, it noted within the soil pedons of gypsum catena with 10-20 cm thick at midslope and downslope. Under moist conditions, the fine earth fraction from the Ap layers (ochric epipedon) of the limestone catena has a color value that ranges from 4 to 8, but the chroma ranges from 2 to 3 (Table 3). The calcareous soils have an equivalent calcium carbonate content of more than 15%, which significantly increases their color values. Additionally, none of ochric horizons defined by USDA Soil Taxonomy system could be considered in the study area based on WRB system. WRB's definition of finely divided lime (WRB, 2022) should be replaced with the total equivalent $CaCO_3$ in the fine fraction of the soil. This contrast is considered in the studied soils classification.

Table 2. Pedomorphological and physical properties of the soils from the limestone catena across wadi El-Ashara study area

Slope position	Horizon suffix	Lower depth, cm	Moist color[1]	Soil structure (Grade, size, type)[2]	Soil consistence (Dry, wet)[3]	Soil pedogenic features [4]	RMF [5]	Root [6]	Gravel (%)	Fine-earth fractions (%)					Texture (USDA)
										Sand			Silt	Clay	
										CS	MS	FS			
Toeslope (P5)	Ap	20	7.5YR 3/2	1, M, GR	S,SO-PO	f,1,CAM	RMX	1, vf	2.05	13.25	17.35	39.45	16.25	13.7	Sandy loam
	Bw	35	10YR 3/2	3, F, ABK	MH,MS-MP	m,1,FDS	CLD	2, vf	1.36	16.35	20.15	20.47	21.04	21.99	Sandy clay
	Btkm	85	10YR 4/1	2, M, MA	SH,SS-SP	m,2, FDS, SAX	FED	1, f	3.54	1.5	4.3	6.7	35.6	51.9	Clay
	Btkz	100	10YR 3/1	3, M, SBK	H, SO-PO	c,1,CAN, FDS, SAX	F3M	None	5.15	7.9	17.6	17.6	29.5	27.4	Clay loam
	Bkm	110	10YR 5/1	2, VF,	VH,SO-PO	f,1, CAN	FMN	None	9.65	11.07	19.14	24.35	20.14	25.3	Sandy clay
	2C	155	7.5YR 6/6	2, F, SBK	VH,MS-MP	f,1,CAN	FMN	None	4.08	15.25	19.04	44.05	11.05	10.61	Sandy loam
Footslope (P4)	Ap	30	7.5YR 4/2	2, M, ABK	SH,SS-SP	f,2,CAN	RMX	2, m	7.25	23.8	34.7	30.1	6.8	4.6	Sand
	2Bd	50	7.5YR 6/8	1, VF, MA	VH,SO-PO	m,1,CAN	CLD	1, vf	45.25	13.6	24.25	25.36	20.14	16.65	Sandy loam
	3Bk	60	10YR 8/4	2, M, ABK	S,SO-PO	c,2,CAN	FED	None	13.05	18.05	19.85	41.07	8.24	12.79	Sandy loam
	4C1	85	10YR 6/8	0, MA	MH,MS-MP	--	F3M	None	10.24	24.15	30.14	28.65	8.15	8.91	Loamy sand
	4C2	130	10YR 6/6	0, MA	S,SO-PO	--	F3M	None	12.05	19.25	33.05	40.15	3.65	3.9	Sand
Backslope (P3)	A	25	10YR 6/8	0, MA	S,SO-PO	m,1, CAN	RMX	1, vf	6.35	10.36	33.05	25.65	11.25	19.69	Sandy loam
	Bk1	50	10YR 6/6	0, MA	SH,SO-PO	m,1,SIC	FED	1, f	4.05	20.15	30.35	19.45	19.25	10.80	Sandy loam
	Bk2	70	10YR 6/6	0, MA	H,MS-MP	f,1,CAN	F3M	None	1.06	8.65	17.25	23.65	21.05	29.40	Clay loam
	Cr	90	10YR 7/6	0, MA	MH,MS-SP	f,1,CAC	F3M	None	3.65	24.16	30.35	9.35	10.50	25.64	Sandy loam
Shoulder (P2)	A	15	10YR 8/3	0, SGR	MH,SO-PO	m,1,CAN	None	None	41.25	20.4	11.35	44.77	7.25	16.23	Fine sandy loam
	C	45	10YR 7/8	0, MA	SH,SO-PO	--	None	None	36.35	45.66	18.45	23.83	8.15	3.91	Coarse sand
Summit (P1)	C	20	10YR 7/6	0, MA	SH,SO-PO	f,1,CAM, SIC	None	None	26.35	35.49	12.05	44.59	5.14	2.73	Coarse sand
	Cr	35	10YR 8/2	0, MA	SH,SO-PO	--	None	None	33.46	16.4	22.15	52.6	6.44	2.41	Sand

Horizon designation suffixes were applied using USDA Soil Taxonomy of Soil Survey Staff (2022) and Schoeneberger *et al.* (2012) manual was used to abbreviate all symbols.

(1) 7/8: yellow, 10YR 6/6, 6/8:brownish yellow, 7.5YR 3/2: dark reddish brown, 10YR 3/2: very dark grayish brown, 10YR 3/1: very dark gray, 10YR 4/1: dark gray, 10YR 5/1: gray, 10YR 7/6, 10YR 8/2, 8/3, 8/4: very pale brown, 7.5YR 4/2: brown, 7.5YR 6/6, 6/8: reddish yellow. (2) ABK: angular blocky, SBK: subangular blocky, GR: granular, SGR:single grain, MA:massive; 0:structureless, 1: weak, 2: moderate, 3:strong; VF:very fine, F: fine, M: medium. (3) S: soft, SH: slightly hard, MH: moderately hard, H: hard, VH: very hard; SO: nonsticky, SS:slightly sticky, MS:moderately sticky, PO:nonplastic, SP:slightly plastic, MP:moderately plastic. (4) f:few, c:common, m:many; 1:fine, 2:medium; FDS:finely disseminated salts, SAX:salt crystals, CAM:carbonate masses, CAN:$CaCO_3$ nodules, CAC:carbonate concretions, SIC:Silica concretions. (5) RMX:reduced matrix, F3M:oxidized iron, Fe^{+3}: masses, Fe^{+3}: stained clay films, FMN:iron-manganese nodules, CLD:clay depletions, FED:iron depletions, 1:few, 2:common; VF:Very fine, f:fine, m:medium.

Table 3. Pedomorphological and physical properties of the soils from the gypsum catena across wadi El-Ashara study area

Slope position	Horizon suffixes	Basal Depth, cm	Moist color [1]	Structure (Grade, size, type)[2]	Consistence (Dry, wet)[3]	Pedogenic features [4]	RMF [5]	Roots[6]	Gravel (%)	Fine-earth fractions (%)					Texture (USDA)
										Sand			Silt	Clay	
										CS	MS	FS			
Toeslope (P10)	Ap	20	7.5YR 4/2	1, M, GR	MH,,MS-MP	f,1, GA, FDG, SAX	RMX	2, m	2.34	5.36	5.16	9.36	52.76	27.36	Silty clay
	Bw	40	7.5YR 6/8	2, F, SBK	VH,VS-VP	f,2, GA, FDG	FMC	2, vf	1.65	3.5	15.02	6.35	35.6	39.53	Clay loam
	Btyz	75	10YR 7/6	2, M, ABK	H,VS-VP	m, 3, GNM, FDS, SAX	--	1, vf	5.08	6.17	6.45	15.04	30.25	42.09	Clay
	Bty	100	7.5YR 3/2	1, M, SBK	VH, MS-VP	c, 2, GA	F3M	None	10.24	9.32	1.05	3.15	48.01	38.47	Silty clay
	Btym	150	10YR 3/2	2, M, ABK	EH,VS-VP	m, 3, GA	RMX	None	19.35	13.65	31.05	9.65	7.50	38.15	Sandy Clay
Footslope (P9)	Ap	15	10YR 8/3	2, F, GR	SH, SS-SP	c, 2, GA, FDG	F3M	2,m	11.25	15.23	17.65	10.24	23.65	33.23	Clay loam
	Bw	35	10YR 6/8	2, F, SBK	H,MS-SP	m, 3, GNM	RMX	1,vf	5.32	20.32	20.35	11.04	19.45	28.84	Sandy clay loam
	By	70	10YR 7/2	0, MA	MH,MS-MP	m, 3, CAM, FDG	RMX	1,f	12.05	25.32	7.65	30.15	30.14	6.74	Sandy Loam
	Cy	110	7.5YR 6/8	0, MA	L ,MS-MP	--	F3M	None	6.32	30.32	20.32	26.35	20.45	2.56	Loamy sand
Backslope (P8)	Ap	10	10YR 7/2	0, MA	H,MS-MP	c, 2, GA, FDG	F3M	1, vf	26.35	3.15	15.02	13.98	50.34	17.51	Silt loam
	Bw	30	10YR 7/2	0, MA	MH,MS-SP	c, 2, GNM	F3M	None	15.34	20.35	21.05	33.15	21.05	4.40	Loamy sand
	Byy	60	10YR 8/4	0, MA	H,MS-MP	c, 2, GA, FDG	F3M	None	24.35	7.15	10.25	29.22	41.32	12.06	Loam
	Cyy	85	10YR 7/2	0, MA	L,SO-PO	--	RMX	None	11.05	5.01	1.02	16.98	62.34	14.65	Silt loam
Shoulder (P7)	A	30	10 YR 6/8	0, MA	SH,SO-PO	m, 1, GA	None	None	12.35	21.35	22.36	32.04	22.11	2.14	Loamy sand
	By	60	7.5YR 8/1	0, SGR	SH,SO-PO	c, 2, GA, FDG	None	None	13.45	43.65	31.05	9.65	9.45	6.20	Loamy sand
Summit (P6)	A	15	10YR 8/2	0, SGR	MH,SO-PO	--	None	None	40.22	30.65	20.65	23.05	11.65	140	Sandy loam
	2Cryy	40	7.5YR 8/1	0, SGR	SH,SO-PO	GYP	None	None	23.06	40.25	31.65	20.35	1.05	6.70	Sand

Horizon designation suffixes were applied using USDA Soil Taxonomy of Soil Survey Staff (2022) and and Schoeneberger *et al.* (2012) manual was used to abbreviate all symbols. (1) 7.5YR 4/2: brown, 7.5YR 3/2: dark reddish brown; 7.5YR 6/8:reddish yellow; 7.5YR 8/1:White; 10YR 7/2: light gray; 10YR 8/2, 8/3, 8/4:very pale brown, 10YR 3/2:very dark grayish brown, 10YR 7/6:yellow, (2) ABK:angular blocky, SBK:subangular blocky, GR:granular, SGR:single grain, MA:massive; grade, 0:structureless, 1:weak, 2:moderate; F:fine, M:medium. (3) L:loose, SH:slightly hard, MH:moderately hard, H:hard, VH:very hard, EH:extremely hard, SO:nonsticky, SS:slightly sticky, MS:moderately sticky, VS:very sticky, PO:nonplastic, SP:slightly plastic, MP:moderately plastic, VP:very plastic. (4) f:few, c:common, m:many; 1:fine, 2:medium, 3:coarse; GYP: rock gypsum; GA: gypsum accumulations; FDG: finely disseminated gypsum; GNM:gypsum crystal clusters; FDS:finely disseminated salts, SAX:salt crystals, CAM:carbonate masses, (5) RMF:redoximorphic features, RMX:reduced matrix, F3M:oxidized iron,Fe^{+3}, masses, FMC:iron-manganese concretions, (6) 1:few, 2:common; VF:Very fine, f:fine, m:medium.

Table 4. Chemical characteristics of the selected pedons on limestone catena of Wadi El-Ashara

Slope position	Horizon	Lower Depth, cm	pH	EC_e (dS/m)	ESP (%)	Gypsum ($CaSO_4.2H_2O$)	$CaCO_3$ (%)	Total SOC (%)[a]	WHC (mm)[b]
Toeslope (P5)	Ap	20	8.51	3.25	8.32	0.10	13.05	1.05	49.32
	Bw	35	8.65	2.06	9.32	1.24	12.34		
	Btkm	85	8.32	10.65	11.05	4.32	35.65		
	Btkz	100	7.99	31.05	2.35	0.24	25.32		
	Bkm	110	8.45	3.65	6.35	0.05	19.35		
	2C	155	7.65	4.35	1.95	0.41	8.20		
Footslope (P4)	Ap	30	8.32	1.35	10.25	1.05	22.32	0.98	37.65
	2Bd	50	9.05	2.65	13.35	2.04	21.32		
	3Bk	60	8.47	1.34	6.41	0.65	25.24		
	4C1	85	8.36	4.95	5.32	7.05	21.32		
	4C2	130	8.32	0.98	1.47	0.65	26.35		
Backslope (P3)	A	25	8.2	0.98	2.34	1.02	21.05	0.51	27.13
	Bk1	50	8.3	1.34	4.19	0.35	33.24		
	Bk2	70	8.9	0.25	19.5	0.47	6.35		
	Cr	90	8.1	0.47	7.01	0.21	4.25		
Shoulder (P2)	A	15	7.96	0.35	6.65	0.34	6.35	0.06	19.32
	C	45	7.36	0.36	4.16	0.16	2.35		
Summit (P1)	C	20	8.01	0.14	9.32	0.34	4.65	0.04	11.04
	Cr	35	7.88	0.21	1.35	0.08	3.75		

Explanation: [a] : Soil organic carbon (SOC) was calculated as a weighted average within 0-≤50 cm; [b]: Water holding capacity was determined within 150 cm or to a lithic contact whichever is shallower.

Table 5. Chemical characteristics of soil pedons from the gypsum catena of Wadi El-Ashara

Slope position	Horizon	Lower depth	pH	EC_e (dS/m)	ESP (%)	Gypsum ($CaSO_4.2H_2O$)	$CaCO_3$ (%)	Total SOC (%)[a]	WHC (mm)[b]
Toeslope (P10)	Ap	20	7.9	15.32	13.35	3.05	5.32	0.95	51.36
	Bw	40	8.1	12.32	5.32	7.35	1.35		
	Btyz	75	8.6	33.65	23.02	21.6	4.36		
	Bty	100	9.1	12.35	17.02	14.32	12.32		
	Btym	150	8.3	10.25	12.05	5.45	2.05		
Footslope (P9)	Ap	15	9.01	7.32	14.35	2.35	1.35	0.75	47.65
	Bw	35	8.75	6.35	6.35	4.15	2.65		
	By	70	7.98	8.65	2.04	21.06	10.24		
	Cy	110	7.45	4.05	1.05	7.12	3.65		
Backslope (P8)	Ap	10	8.32	1.05	11.35	6.34	4.02	0.41	34.98
	Bw	30	8.15	3.65	4.25	45.75	5.32		
	Byy	60	8.62	5.32	5.65	63.51	1.05		
	Cyy	85	7.68	4.05	3.15	54.11	1.36		
Shoulder (P7	A	30	8.05	2.35	11.05	34.47	2.35	0.31	30.5
	By	60	8.01	1.08	10.24	45.24	0.65		
Summit (P6)	A	15	8.31	0.98	9.35	4.89	1.05	0.02	15..08
	2Cryy	40	7.35	0.14	8.35	61.35	0.0		

Explanation: [a] : Soil organic carbon (SOC) was calculated as a weighted average within 0-≤50 cm; [b]: Water holding capacity in mm/1.5 m soil depth or to a lithic contact whichever is shallower.

In terms of soil color and the action of bleaching chemicals, gypsum content can lighten the color of the matrix in a similar way to $CaCO_3$, although the existing taxonomies do not account for it. In this way, some ochric horizons described in gypseous soils could be called ochric if the bleaching activity of gypsum was also included. Furthermore, some soils and sediments have more than 40% gravel or coarse fragments at 100 cm depth of the soil pedon surface, and thus qualify Skeletic suffix for the WRB system.

Cambic horizon

A cambic subsurface horizon is formed as the result of pedogenic alterations, removals, and transformations combination processes. The altered cambic horizon (Bw) of 15 cm thick is formed at downslope (Toeslope) of limestone catena and it reached 30 cm in gypsum catena at both backslope and toeslope. The Bw-horizon of the limestone catena exhibited extensive alteration leading to formation fine stratifications, mineral subsurface horizon with a strong angular blocky structure and absence of rock structure. It has both low color values and low chroma due to the high total lime content. This horizon is characterized by relative removal of carbonates or gypsum. In studied weathered limestones, there is an increase in color and the development of soil structure. Silty layers overlaying shist fragments show the development of soil structure and the accumulation of iron compounds. All of the requirements for a cambic horizon were reported in the above mentioned subsurface horizon in soils of Wadi El-Ashara.

Calcic horizon

Calcic horizons (Bk1 and Btkm) were only observed in backslope (P3) and toeslope (P5) positions and it was absent in footslope position across limestone catena. The Btkm horizon is a 50 cm thick with numerous plainly visible secondary carbonates that contains 35.65% calcium carbonate. Several secondary carbonate concentrations of different shapes were found within most slope positions of the limestone catena and toeslope position of gypsum catena (Figs. 8 & 9) but it didn't fit the requirement of calcic horizon. Calcic horizons are abundant in mature soils in arid climate plains (Badía *et al.*, 2013). The USDA Soil Taxonomy system identifies a calcic horizon based on the concentration of equivalent calcium carbonate within soil pedon layers (Bateman *et al.*, 2019), whereas the WRB approach identifies the calcic horizon based on finely divided lime, commonly known as "active $CaCO_3$" (Delbecque *et al.*, 2022). The USDA Soil Taxonomy (Soil Survey Staff, 2022) and the WRB (2022) have the same diagnostic criteria for calcic horizons; it has a thickness of ≥15 cm and contains ≥15% calcium carbonate as well as ≥5% by volume secondary carbonates than the underlying horizon/layer.

Gypsic horizon

The required characteristics of gypsic horizon are same for both IUSS WRB and USDA soil taxonomies. Gypsic horizons were recognized in all slope positions of gypsum catena except of summit slope position (Fig. 9 & Table 5). The accumulation of secondary gypsum can be visible in form of light color dots–concretions. Non-cemented surface or subsurface horizons containing accumulations of secondary gypsum in various forms were observed in most soils across gypsum catena except summit slope position. In the gypsum catena, the colluvial soils of C-2Cryy sequence (P6) at the summit are distinguished by substantial accumulations of primary gypsum without formation of a gypsic horizon. The soils of backslope (P8) include Ap–Bw-Byy-Cyy horizon sequence while the alluvial soils of footslope (P9) and toeslope (P10) have Ap-Bw-By-Cy and Ap-Bw-Btyz-Bty-Btym horizon sequences, respectively as shown in Tables (3 & 5) and Fig. (9). According to the WRB system's basic criteria, the Byy (30-60 cm) of P8 at the backslope contains enough gypsum (63.51%) to classify the horizon as hypergypsic (Table 5). Casalini and Bisigato (2017) proved that gypsic horizons can be formed by altering gypsum rock in situ. Under these conditions, even the By horizon of P7 on shoulder, with 45.24% $CaSO_4.2H_2O$, may be regarded a gypsic horizon due to pedogenic gypsum accumulation (Table 5& Fig. 9).

The WRB (2022) used a broader range of classification nomenclature for gypseous soils than the USDA Soil Taxonomy system, based on gypsum concentration within soil pedon. The WRB employs hypogypsic (less than 25% gypsum) and hypergypsic (more than 50% $CaSO_4.2H_2O$ within 100 cm of the soil surface). It also signifies gypsiric material (≥5% $CaSO_4.2H_2O$ within 100 cm, >30 cm thick and missing a gypsic or petrogypsic horizon) and gypsic horizon containing ≥5% $CaSO_4.2H_2O$ and ≥1% visible secondary gypsum, with a product gypsum concentration and thickness of 150 or more. Soils derived from gypsum catena, such as those analyzed here, simply exceed the 5% $CaSO_4.2H_2O$ threshold. Gyprock or gypsum rock and pedogenic gypsum are terms used to differentiate between gypsic rocks (Ríos *et al.*, 2018). Furthermore, a simple and accurate method for determining gypsum content in soils should be chosen. According to current study, lime, gypsum, and salts leached from high altitudes of mountain landforms are transferred lower to form calcic and gypsic or salic layers. As a result, slope position and parent material had a significant impact on Wadi El-Ashara soil attributes.

Salic horizon

In limestone catena, an accumulation of soluble salts with EC_e of 31.05 dS m^{-1} was observed within 85-100 cm depth as subsurface horizon in pedon 5 (P5). A product of this horizon thickness and EC_e value was found to be 465.75 (Table 4& Fig. 8). This qualifies the requirements of a salic horizon in WRB system but not qualify by USDA soil taxonomy manual. To define a salic horizon, the USDA taxonomy technique requires an EC_e of at least 30 dS m^{-1} with a thickness horizon of at least 15 cm and a product greater than 900, whereas the WRB system needs an EC_e of $\geq$15 dS m^{-1} with the same horizon thickness ($\geq$15 cm) and a product greater than 450.

On the other hand, soils of gypsum catena have an accumulation of soluble salts (33.65 dS m^{-1}) in the subsurface Btyz horizon (40–75 cm) of pedon 10 (P10) at toeslope position (Table 5& Fig. 9). This horizon was defined as a salic horizon by both WRB and USDA Soil Taxonomy systems.

Soil Taxonomic Interpretation

Table (6) compares soil classification and types across limestone and gypsum catenas using the USDA Soil Taxonomy of Soil Survey Staff (2022) and WRB (2022) systems. Soils in limestone catena are classified as *Entisols* and *Aridisols* by the USDA Soil Taxonomy and can be distinguished by the formation of subsurface diagnostic layers. *Torripsamments* and *Torriorthents* were the dominant great groups of *Entisols* with significant variances due to their positioning on different slope positions within the catena; i.e., *lithic, leptic, and typic* (Table 6). Based on the presence of calcic and salic horizons, the soils of P5 at toeslope position was classified as *Typic Haplocalcids* according USDA soil taxonomy, and *Haplic Calcic Yermic Solonchaks (Siltic, Aeolic, Ochric*) according to WRB (Table 6). The soils of *Entisols* order in USDA soil taxonomy perform to be identical to *Leptosols* and *Arenosols* as reference soil groups (RSG) of the WRB system. According to USDA soil taxonomy, soils of limestone catena at the summit (pedon 1; P1), shoulder (pedon 2; P2), backslope (pedon 3; P3), footslope (pedon 4; P4), and toeslope (pedon 5; P5) belong to the subgroups of *Lithic Torripsamments, Lithic Torriorthents, Sodic Haplocalcids, Typic Torriorthents, and Typic Haplocalcids*, respectively. Whereas the same soils were classified based on WRB system as *Lithic Calcaric Leptosols (Arenic, Aridic, colluvic)*, *Lithic Calcaric Skeletic Leptosols (Aridic, colluvic)*, *Haplic Yermic Calcisols (Loamic, Aeolic, Sodic*), *Aeolic Calcaric Yermic Arenosols (Claric*), and *Haplic Calcic Yermic Solonchaks (Siltic, Aeolic, Ochric*) for soils from upslope to downslope, respectively (Table 6 & Fig. 8).

As stated by the USDA Soil Taxonomy system, soils of the gypsum catena belong to the suborder *Orthent* at summit, *Gypsids* at shoulder, backslope, and footslope, and *Salids* at toeslope. The detected lithic contact and aridic moisture regime define the summit soil as *Lithic Torriorthents* subgroup by USDA Soil Taxonomy system or *Gypsiric Nudilithic Skeletic Leptosols (Yermic, Colluvic)* by WRB. On the other hand, soils of gypsum catena from upslope to downslope can be classified according to USDA Soil Taxonomy system as *Lithic Torriorthents, Leptic Haplogypsids, Leptic Haplogypsids, Typic Haplogypsids, Typic Haplogypsids,* and *Gypsic Haplosalids* based on the presence of gypsic horizons within 30-100 cm of the soil surface (Table 6). Whereas the soils from upslope to downslope on gypsum catena were also classified based on WRB system as *Gypsiric Nudilithic Skeletic Leptosols (Yermic, colluvic), Leptic Haplic Gypsisols (Arenic), Leptic Haplic Gypsisols (Siltic, Aeolic), Leptic Haplic Gypsisols (Loamic, Aeolic, Gypsic Yermic Solonchaks (Clayic, Gypsiric).* Soil texture was considered in the WRB system as supplementary qualifiers and explains the soil types across slope positions of the studied catenas. The upslope soils (summit or shoulder) were dominated by arenic and colluvic materials in both catenas, whilst siltic or clayic soils were found in toeslope positions (Tables 2, 3 & 6).

The parent material and slope position were identified as the two most important soil forming factors impacting the soil parameters and characteristics of Wadi El-Ashara. Additionally, this work demonstrates that the most recent versions of the WRB (2022) and USDA Soil Taxonomy of Soil Survey Staff (2022) systems contain certain inconsistencies in the classification of arid-zone soils. When the two taxonomic approaches are applied to the same soil horizons, differences in diagnostic property measures provide the same taxa to horizons with differing characteristics, or vice versa.

Table 6. Soil classification types based on USDA Soil Taxonomy of Soil Survey Staff (2022) and WRB (2022)

Parent rock catena	Slope position	Soil type classification	
		USDA soil taxonomy (Subgroup level)	**WRB soil classification (Reference soil groups)**
Limestone	Summit(P1)	*Lithic Torripsamments*	*Lithic Calcaric Leptosols (Arenic, Aridic, Colluvic)*
	Shoulder (P2)	*Lithic Torriorthents*	*Lithic Calcaric Skeletic Leptosols (Aridic, Colluvic)*
	Backslope (P3)	*Sodic Haplocalcids*	*Haplic Yermic Calcisols (Loamic, Aeolic, Sodic)*
	Footslope (P4)	*Typic Torriorthents*	*Aeolic Calcaric Yermic Arenosols (Claric)*
	Toeslope (P5)	*Typic Haplocalcids*	*Haplic Calcic Yermic Solonchaks (Siltic, Aeolic, Ochric)*
Gypsum	Summit (P6)	*Lithic Torriorthents*	*Gypsiric Nudilithic Skeletic Leptosols (Yermic, Colluvic)*
	Shoulder (P7)	*Leptic Haplogypsids*	*Leptic Haplic Gypsisols (Arenic, Aeolic)*
	Backslope (P8)	*Typic Haplogypsids,*	*Leptic Haplic Gypsisols (Siltic, Aeolic)*
	Footslope (P9)	*Typic Haplogypsids*	*Leptic Haplic Gypsisols (Loamic, Aeolic)*
	Toeslope (P10)	*Gypsic Haplosalids*	*Gypsic Yermic Solonchaks (Clayic, Gypsiric)*

Leptic in WRB system: Soils have continuous rock within soil pedon at ≤ 100 cm from the soil surface; Leptic in USDA soil taxonomy: Thin soil.

CONCLUSIONS

The following are the key findings of the current study:

- Soil pedomorphological, physicochemical, and formation features of soils on distinct landforms in two catenas of Wadi El-Ashara were shown to be strongly impacted by their geomorphic position.
- From upslope to downslope along two analyzed catenas, soil salinity rose in the toeslope. Saline soils with lime or gypsum accumulations showed higher salinity of up to 31.05 dS m^{-1} in the Btkz horizon in limestone catena and 33.65 dS m^{-1} in the Btyz horizon in gypsum catena generating salic horizons based on WRB diagnostic criteria.
- The presence of calcic, salic, sodic, and gypsic horizons in the studied piedmont plain and basin floor soils with an aridic soil moisture regime indicated a similar or different classification when using WRB and USDA taxonomies.
- The investigated soil-geomorphic components and linkages revealed a variety of interactions among Jenny's five soil-forming factors. The current study demonstrated how a change in one soil-forming factor can cause the entire desert ecosystem to respond. A greater knowledge of soil-geomorphic processes and how they interact on a broader scale will help to explain and control the variability found in dry ecosystems worldwide.
- The soil-geomorphic pattern provides a framework for integrating criteria from various disciplines, including climatology, soil science, landscape, geomorphology, organismal ecology, and ecosystem ecology.
- Geomorphology affects soil morphological parameters (RMF, consistency, structure, and horizontation), particle size distribution, and soil chemical values (pH, gypsum, and $CaCO_3$). Land use predominantly influenced the topsoils of the examined pedons (soil pH, root abundance, SOC content, and soil structure), as well as the properties of RMF in the downslope pedons. The study concluded that geomorphology and slope position had significant impacts on soil formation in both transects along two catenas of Wadi El- Ashara. Soils on the summit slope are underdeveloped, while soil formation with calcic and gypsic layers is possible on intermediate slopes due to the smoother topography.
- The key component that explains the classification of the investigated soils is parent material type (mostly *Torripsamments* or *Torriorthents* and *Haplocalcids* or *Haplosalids* on limestone catena

and *Haplogypsids* or Torriorthents on gypsum catena). However, topography impacts some parameters that govern soil classification, such as effective soil depth (*Leptic* or *Lithic* qualifiers).

- The limestone catena possessed an ochric epipedon that lacked both rock structure and finely stratified fresh deposits. According to USDA Soil Taxonomy system criteria, these criteria allowed for the determination of a diagnostic surface horizon of an ochric epipedon. Furthermore, the USDA technique employs the concept of total $CaCO_3$, whereas WRB system employs the finely divided lime fraction term. Secondary enrichment of additional chemicals, as in the case of calcic, gypsic, and salic horizons, can similarly confuse classifications based on soil composition.
- In terms of EC criteria and product of thickness, the concept of a salic horizon differs between WRB (2022) and USDA Soil Taxonomy of Soil Survey Staff (2022) recommendations. In a common system, these requirements may be reconciled.
- Based on the foregoing, more interpretation and debate are required to develop the soil taxonomy systems currently in use and finally reconcile them into a Universal Soil Classification Scheme.

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الملخص العربي

تأثير الوحدات الجيومورفولوجية على صفات التربة بوادي العشرة، غرب قناة السويس، مصر

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تعكس عوامل تكوين التربة Soil forming factors العديد من خصائص التربة وعمليات تكوينها. كان الهدف من هذه الدراسة هو تقييم تأثير الوحدات الجيومورفولوجية والمعايير ذات الصلة لمادة الأصل وطبوغرافية سطح التكوين الأرضي Topography of landform على خواص التربة وتكوينها في وادي العشرة، غرب قناة السويس، مصر. تم دراسة أنواع وخصائص التربة المختلفة وتقسيمها بوادي العشرة عبر نوعان من المتسلسلات الأرضية Soil catenas، وهما المتسلسلة الأرضية الكالسية Limestone catena، وكذلك المتسلسلة الأرضية الجبسية Gypsum catena. تم استخدام بعض الأنظمة الدولية لتقسيم التربة في كلتا المتسلسلتين وهما النظام الأمريكي لتصنيف التربة USDA Soil Taxonomy of Soil Survey Staff، والنظام الدولي الذي يمثل القاعدة المرجعية العالمية لموارد التربة World Reference Base (WRB). ولتحقيق أهداف الدراسة، تم التعرف على الصفات البيدومورفولوچية والفيزيائية والكيميائية للتربة من خلال دراسة عشرة قطاعات تربة ممثلة لكافة الوحدات الچيومروفولوچية والتكوينات الأرضية عبر مواقع الانحدار المختلفة Slope Positions لكل متسلسلة أرضية Soil Catena، وهي Summit, Shoulder, Backslope, Footslope, Toeslope. حيث تم تمثيل خمس قطاعات تربة خلال مواقع الانحدار لكل متسلسلة أرضية، وذلك لتمثيل الوحدات الأرضية بمواقع الانحدار العليا Upslope positions والتي تتضمن الوحدات الأرضية للجبال Mountain landforms مروراً بمواقع الانحدار الوسطى Midslope positions، إلى مواقع الانحدار السفلى Downslope positions ممثلاً للتكوينات الأرضية Piedmont و Basin floor.

أوضحت النتائج أن قيم الملوحة الأرضية اختلفت طبقاً لمواقع الانحدار وطبوغرافيته حيث زادت درجة الملوحة كلما قل الانحدار بمواقع الانحدار السفلى Downslope ذات الانحدار المنخفض. بالإضافة إلى تكوين بعض الآفاق التشخيصية مثل الآفق الكالسي بالمتسلسلة الأرضية الكالسية Limestone Catena، والآفاق الجبسية بالمتسلسلة الأرضية الجبسية Gypsum Catena مع وجود الآفق الملحي في كلتا المتسلسلتين. وبتطبيق الأنظمة الدولية لتصنيف التربة، فقد قسمت أراضي المتسلسلة الكالسية طبقاً للنظام الأمريكي USDA soil taxonomy إلى خمس أنواع من التربة عبر المتسلسلة الأرضية من Upslope إلى Downslope وهم كالتالي:

Lithic Torripsamments, Lithic Torriorthents, Sodic Haplocalcids, Typic Torriorthents, Typic Haplocalcids

في حين أنه تم تقسيم نفس الأراضي إلى أربعة مجموعات مرجعية Reference Soil Groups (RSG) طبقاً للنظام الدولي WRB وهم: *Leptosols, Calcisols, Arenosols,* and *Solonchaks* (بخلاف Principal and supplementary qualifiers)، ولقد لوحظ وجود الأفق الملحي بأراضي Toeslope طبقاً للنظام الدولي WRB حيث تم تصنيف التربة بهذا الموقع ك *Solonchaks* . ولكن طبقاً للنظام الأمريكي لا يوجد متطلبات هذا الأفق ولذلك تم تصنيف نفس التربة ك *Haplocalcids*، ولهذا فإنه يوجد قصور في تلك الأنظمة لعدم تعريف الأفق الملحي بمعايير

تشخيصية مُحددة، ولكلا منهما معايير تعريفية له مختلفة عن الأخر.

وبالنظر إلى أنواع الأراضي الأخرى والتي تكونت على مادة أصل جبسية، فقد تم تقسيمها طبقاً للنظام الأمريكي كالتالي:

Lithic Torriorthents, Leptic Haplogypsids, Typic Haplogypsids, Gypsic Haplosalids

بينما قُسمت نفس الأراضي طبقاً للنظام الدولي WRB إلى ثلاثة محموعات RSG وهم: *Leptosols, Gypsisols, and Solonchaks*. وبالنظر إلى أنواع التربة بكل متسلسلة أرضية Soil Catena يلاحظ وجود اختلافات كبيرة فيما بينهم، وأن لمواقع الانحدار Slope position وطبوغرافية سطح التكوين الأرضي Topography ومادة الأصل Parent material التي تكونت منها المتسلسلة الأرضية Soil Catena دوراً هاما ومؤثرًا في توزيع وتصنيف التربة عبر المتسلسلات الأرضية التي تم دراستها بوادي العشرة، بالإضافة إلى أن نتائج الدراسة كشفت بعض القصور في الأنظمة الدولية وخاصة في تعريف بعض الآفاق التشخيصية وخاصة الآفق الملحي Salic horizon، مما يستدعي إبتكار وتطوير نظام تقسيمي عالمي Universal Soil Classification System موحد فيه المعايير التشخيصية لمواد وآفاق التربة المختلفة لمعرفة وتصنيف أنواع التربة بشكل سليم.