

Surface Geomorphological Processes that Determine the Morphology of the Slopes of the Western Valleys in Wadi Al-Qa' – Jordan

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Abstract
The aim of this study is to analyze the surface geomorphological processes that contribute to the formation and evolution of the morphology of the western slopes of Wadi Al-Qa'. These processes are: the forces of water erosion; and the mass wasting and rock fall on slopes surfaces. This study also aims at analyzing the rocky structure of the slopes and other environmental conditions that have an impact on determining the morphological shape of the slopes. The methodology of the study relied on conducting many field measurements; the most important of which were measuring the volume of sediment deposited at the bottom of the slopes, and measuring the morphometric characteristics of the western slopes. The study results showed that the dynamics of the evolution and development of the western slopes morphology is associated with the basin changes imposed by the geo-morphodynamic processes that are prevailing in the upper basin of the Valley. The most important of which are water shearing force which the western slopes are subjected to during rainy periods, as well as being subjected to tectonic movements resulting in collapse of lateral slopes of valley. The study also shows the role of the gradient in development of slopes morphology as rock fall and mass wasting processes are more active in the slopes that have a gradient of more than 10° as they constitute 74.4% of the total rock fall and mass wasting.
Keywords: Wadi AL--Qa', Slopes morphology, Geomorphological processes, Water erosion.

1. Introduction:

Specialists in the field of earth sciences focused in their studies of the slopes of the valleys on the relationship between gradient and runoff volume on the one hand, and the rate of soil erosion on the other hand (Watson and Laflen, 1986; Fox and Bryan, 1999; Dennis and Rorke, 2000; Suhua, 2011; Jochem and Daan, 2014).These studies proved that the rate of soil and surface materials erosion increases mainly on the slope sides as a result of the interaction of numerous natural variables. These variables include the increase in water discharge volume, the increase in the surface gradient, the decrease in vegetation, and the looseness of soil. These variables directly weaken the soil and surface resistant of water shear forces. Hence, the result is the deterioration of soil characteristics and the appearance of the rocky outcrops which are exposed to mechanical weathering.

Some recent studies focused on natural problems and hazards which are formed on both sides of the slopes of the valleys, the most important of which are landslides, rocks fall, soil erosion and interrill erosion (Cruden, 1985; Bradford and Foster, 1996; Evans and Degraff, 2002; Assouline and Ben-Hur, 2006; Hewitt, 2006). Most of these studies overlooked the role of surface surface geomorphological processes that determine the morphology of the slopes of the Valleys.

The morphological evolution of slopes of the valleys is considered as a product of a series of overlapping surface geomorphological processes, the most important of which are the water erosion processes, the weathering processes, and the mass wasting processes. The slopes of the valleys differ in their morphological characteristics depending on the circumstances of their evolution and development, as those characteristics shed light on the most important geomorphological factors and processes through which those slopes have evolved, and on their associated environmental and geomorphological implications.

The geomorphological importance of examining the slopes of the western valleys in Wadi Al-Qa' lies in their variable dynamic nature which is an outcome of the prevailing basin environment. This basin environment is represented by the climatic conditions, geological features, the morphology of the surface, and the degradation of the vegetation; as these factors interact with each other to contribute to the determination and the development of the morphological characteristic of those slopes.

Hence, the study of the morphological characteristics of those slopes and their associated geomorphological implications will contribute to determining the changes they are exposed to, and their spatial extension. This paves the way to develop appropriate solutions to reduce their negative effects on soil and agricultural projects exerted on the surfaces of the western slopes of Wadi Al-Qa'.

2. Methodology and methods:

The study adopted two approaches, namely: the practical approach and the analytical approach. The practical approach is represented in conducting many field measurements, which lasted from October 2013 until April

2014.

Those measurements included measuring the volume of sediment deposited at the bottom of ten slopes. Measurements related to the Morphometric characteristics of the western slopes were conducted in terms of the average of their gradient, shape, and length.

The practical approach also included measurement of the morphometric characteristics of rills in terms of the average of their density, width, depth, distance between rills, and length. This study relied on the system of the Faculty of Geo-Information Science and Earth Observation (ITC) in determining the morphometric characteristics of the rills and their erosive effectiveness. According to that system, the depth of rills is less than 50 cm. The erosive effectiveness of the rills is classified according to the distances that separate them from each other within the following categories:

1. Medium erosion category (less than 20 cm).
2. Light erosion category (20-50 cm), (Zuidam, 1979).

The analytical approach has focused on the analysis of data derived from field measurements, in addition to the analysis of the morphometric characteristics that have been extracted from the topographic maps scale (1 - 50000) for the year 2007, and aerial photographs scale (1-25000) for the year 2010.

The morphology of the western slopes of the valleys in Wadi Al-Qa' has been extrapolated by using the above mentioned two approaches.

3. The Physical Characteristics of the Basin:

The basin of Wadi Al-Qa' is located in the southwestern part of the Hashemite Kingdom of Jordan between longitudes 35˚ 29 and 35˚ 48 east; and latitudes 30˚ 15 and 30˚ 20 north. The maximum length of the basin is 26.6 km from east to west, while it extends 11 km from north to south, with an area of 220.6 km^2 (Figure 1).

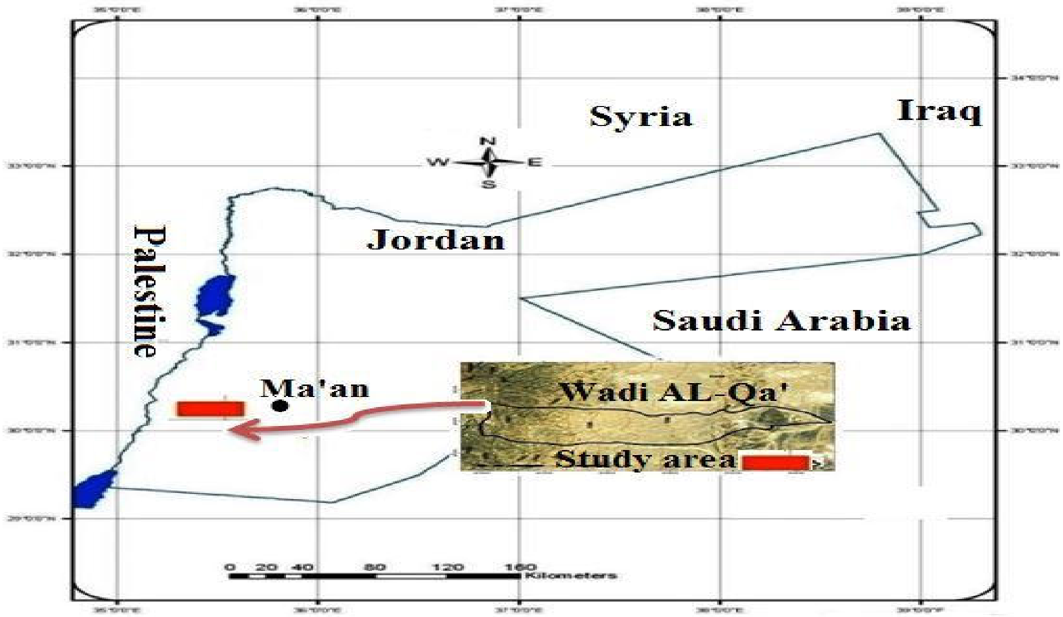

Fig 1. The boundaries of study area

The changes in the physical characteristics of the basin elements make constant changes in the morphology of the slopes. The physical characteristics of Wadi Al-Qa' are: the climate, the geology, the vegetation, and the soil. These characteristics have a direct impact on the evolution of the slopes. The increase in the amount of rainfall in the upstream area (200 mm) and its concentration in the winter where the rate of temperature falls down to (7º C) raise the amount of water discharge of runoff water on the surfaces of the slopes; hence, increasing its erosion forces and its ability to make constant changes to the morphology of the slopes. On the other hand, the low rate of rainfall in the lower areas of the basin has reduced the effectiveness of the runoff water in developing slopes in those areas.

As for the geology of the basin, there are two major formations that predominate in the western headwaters area: the formation of Wadi Al-Seer (A7) and the formation of Amman (B2). The formation of Wadi Al-Seer consists mainly of lime-dolomite rocks, which is characterized by medium permeability. These formations have been exposed to fractal movements and weathering processes which have contributed to increase their permeability. The formation of Amman consists of limestone, flint stone and phosphate stone. This formation is characterized by a large number of cracks and joints that have contributed directly to weakening its components, thus, making it vulnerable to water erosion forces (Figure 2). This formation goes back to the

Campanian Age (Bender, 1974).

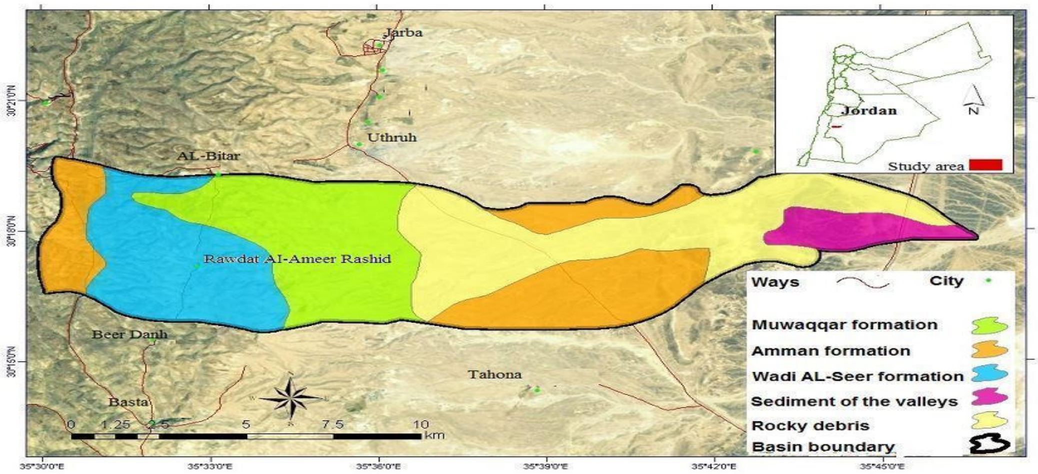

Fig 2.Surface formation in Wadi Al-Qa' basin.

The vegetation has emerged as a geomorphological factor. It has an influential role in the stability of the slopes' morphology; as the vegetation extending along some slopes forms a natural obstacle against runoff waters which weakened its capacity in eroding the components of the surface of the slope. The vegetation also plays a role in strengthening the cohesion of the components of the slope materials, and increasing the coefficient of water leakage, which ensures the existence of an inverse relationship between vegetation and the erosive ability of the runoff waters (Hany et al.,2013). The rate of vegetation in the western slopes ranges between 0 - 13.6% .

As for the soil, there are two types of soils covering the western slopes in the headwaters area, namely: Xerochreptic Calciorthid and Calcixerollic Xerochrept (Ministry of Agriculture, 1993).

The estimated areal extension of Xerochreptic Calciorthid is around 87% of the area of the western slopes. It is characterized by its coarse, loamy-sandy texture and its weak structure which weakens its ability to resist the forces of erosion by water flows that forms in the upper basin area after rainfall. The Calcixerollic Xerochrept is located within the semi-dry moisture pattern, and spreads over an area of approximately (13%) of the area of the western slopes. It is characterized by its loamy-muddy texture. And because of its good physical characteristic due to the increased rates of rainfall on the upper basin area, it is subjected to agricultural works by the inhabitants of the region. This, in turn, made it vulnerable to erosion processes by water flows.

4. Results and discussion

4.1 .Surface Geomorphological Processes:

4.1.1. The role of water erosion in the formation of the morphology of the western slopes of the valleys:

The western headwaters area in Wadi Al-Qa' is characterized by a relatively rough topography, as its relief ratio is (18 m/ km). This topography enhances the forces of water erosion to form and develop the western slopes through its direct impact on the characteristics of water flows which remove the materials that make up those slopes (Figure 3).

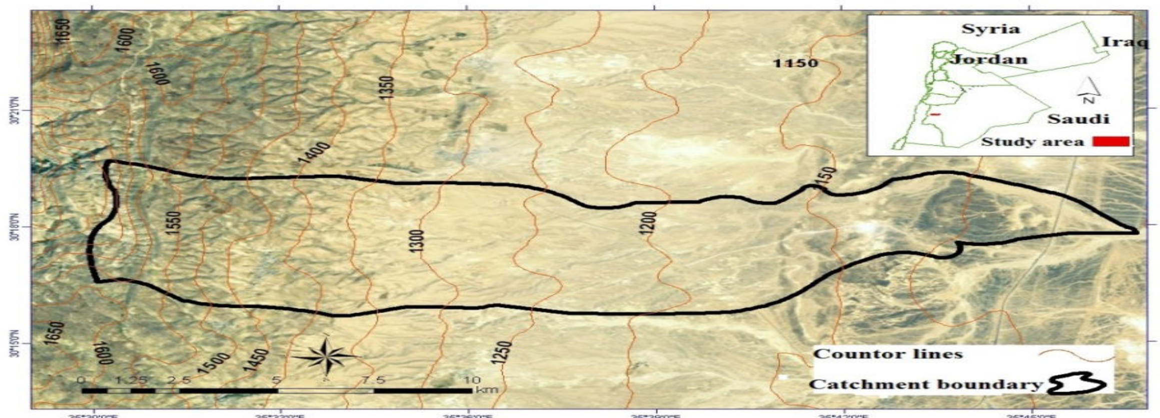

Fig 3.The topography of Wadi Al-Qa'

The water erosion processes are also affected by the shape properties of the slopes; the degree of their surfaces roughness and the degree of coherence of the components of the slopes materials. While the water flow has a direct effect on the evolution of the shape of the slopes, we find that the shape of the slopes, the degree of cohesion, and the degree of roughness, affect the characteristics of the water flow. The concave slopes increase the vertical erosion processes of water flow, due to their increased gradient compared with the convex slopes. Moreover, the difference in homogeneity of the materials on both sides of the valley determines the morphology of the slopes; slopes that consist of non-cohesive material are susceptible to more water erosion processes than the cohesive slopes.

The effect of the roughness of slope surface on the erosive ability of water flow is evident after removing vegetation. Vegetation removal makes the surface less rough, which increases the flow velocity and its erosive ability. On the other hand, we find that the mechanism of slopes erosion affects their surface morphology, their roughness and their development; due to the different mechanisms that can lead to different patterns of regressive erosion of the slopes. The rate of slopes retreat increases with the increase of shear forces affecting them and their gradient. Furthermore, vegetation removal makes the concave slopes much steeper; while convex slopes are more stable, and this in turn leads to a decline in the concave slopes.

Table (1) shows the thickness of the layer removed from the slopes of the western valleys during two rain storms on the basin. It is clear from the analysis of the table that:

1. The thickness of sediment eroded and deposited down those slopes increases with the increase in the gradient. We find that the slopes marked by a significant increase in their gradient have recorded the highest values of the thickness of sediment eroded and deposited; this is clearly shown in the slopes (1, 2 and 3), where the rate of thickness of sediment removed from these slopes during the first and second storms ranged between (12.5 mm - 13.9 mm) and (8 mm – 8.5 mm) respectively, while the gradient of these slopes ranged between (7.5^{o} - 12.5^{o}). The slopes characterized by low gradient have recorded low rates of thickness of sediment removed; this is clearly shown in the slopes number (8, 9, 10), where the rate of thickness of sediment removed from these slopes during the first and second storms ranged between (5.5mm - 6.5 mm) and (3 mm - 5.5 mm) respectively, while the gradient of these slopes ranged between (4^{o} - 6.5^{o}).
2. The increase in the erosion rates is associated with a decrease in vegetation ratio, which ranged between (4.5% - 9%) with an average of (6.25%). The low density of vegetation in those areas has resulted in a marked increase in the amount of eroded materials with low cohesion and low ability to resist erosion factors.
3. The high volume of rainfall increases the effectiveness of water erosion through the disintegration of the components of the surface by raindrops, and the increase in the volume of water flow (Meyles et al.,2002; Kinnell, 2005). The rate of sediment removed from the slopes during the first and the second storm has reached (9.05 mm, 6.3 mm) respectively, while the total volume of rainfall in those storms has reached (50 mm, 20 mm) respectively.
4. The increase in the area of the rocky outcrop is an evidence of the effectiveness of water erosion in the removal of the surface components of the slopes. The percentage of the rocky outcrop ranged between 2% in slope (9) and 17% in slope (1).
5. The shape of the slope affects the effectiveness of water erosion. Hence, concave slopes respond to water erosion in a much more degree than the convex slopes. The rate of thickness of sediment removed from concave slopes during the first and second storms ranged between (7.5 mm - 13.9 mm) and (6 mm - 8.5 mm) respectively, while the rate of thickness of the sediments removed from convex slopes during those storms ranged between (5.5 mm – 9 mm) and (3 mm - 7.5 mm) respectively.
6. The processes of erosion are affected by the length of the slope. The increase in the length of the slope increases the efficiency of water erosion, as the increase in the length provides an increase in the amount of water running on the surface of the slope. This is clearly shown in slopes (1, 2, 3 and 4).

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Table 1. shows the thickness of sediment measured at the bottom of the slopes of the western valleys after being hit by rain storms during the rainy season 2013 - 2014.

Slope number	The characteristics of the slope					Area of measured region / m^2	Average thickness of sediment deposited / mm	
	Gradient	Shape of the slope	Length of the slope / m	The rate of emergence of the rocky outcrop %	Vegetation ratio%		The first storm 11-14 - 12-2013 *(50 mm)	The second storm 6-9-1-2014 *(20 mm)
1	12.5	Concave	1200	17	4.5	16	13.9	8.5
2	9	Concave	900	14	4	16	12.6	8
3	7.5	Concave	1200	11	5	16	12.5	8
4	5.1	Convex	500	8	5.5	16	9.5	7.5
5	4.8	Convex	600	3.5	7	16	9	7
6	6.4	Concave	650	4	6	16	7.5	6
7	6.5	Concave	700	5	5.5	16	8	6.5
8	6.5	Convex	400	5.5	7	16	6.5	5.5
9	4	Convex	525	2	9	16	5.5	3
10	4.6	Convex	390	2.5	9	16	5.5	3
Average	6.69			7.25	6.25	16	9.05	6.3

*Total volume of rainfall in storm

The effectiveness of water erosion in forming the western slopes increases with the regularity of the rills that have varying morphometric characteristics. Table (2) shows the morphometric characteristics of the rills. The following facts are extrapolated from this table:

1. The density of rills increases with the increase in the gradient of the surface. The density of rills on a slope with a gradient of 12.5 ^{o} reached about 3.5 / m^2, while the density decreased to 1.7 / m^2 in the rills with a gradient less than 4 ^{o} . This is due to the increase of the effectiveness of runoff on the surface incision with the increase in the gradient, as the increase in the gradient leads to an increase in the competence and energy of runoff to carry out the erosion processes and incision on the surface of the slope.
2. Rills in the denudation slopes appear close to each other. The degree of convergence increases as we move toward the northwestern areas within the upper basin, due to the high rates of rainfall and the activity of agricultural operations in those areas. The slopes (1, 2, and 3) represent those areas where the average distance separating the rills from each other in these slopes is (9.8 cm, 8.7 cm, 7.8 cm). The convergence of rills indicates the degree to which the north-western slopes are influenced by erosion processes. Using the criteria of (ITC) to determine the degree to which the slopes are affected by erosion due to rills, we find that they fall into the medium category: less than 20 cm. The convergence of rills speeds up their meeting process after rainstorms, leading to trenching the surface of the slope, and eroding its rocky components, which in turn reduces the ability of water to make its way to the lower layers. The density and convergence of rills have reached their minimum limits in the slopes near the eastern areas of the basin, which are represented by the slopes (7, 8, 9 and 10). The average distance between the rills in these slopes reached (17 cm, 11.2 cm, 19.2, cm and 15.2cm) respectively. This is due to the low rates of rainfall on those areas, which range between (100 - 200) mm (Figure 4).

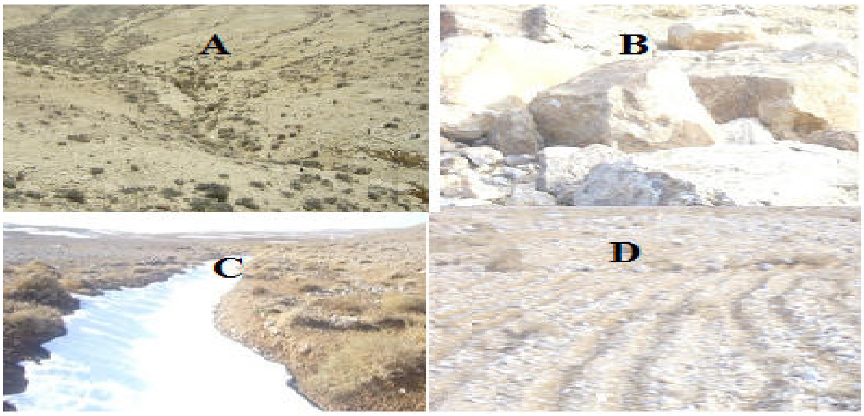

Fig 4. A: Rills density on the western slopes in Wadi Al-Qa' B: Mass wasting and rock fall on the western slopes C: The role of water erosion in trenching the surfaces of the western slopes during the snowstorm 11/12/2013 D: Tilling the western slopes of the region's population.

On the other hand, the average distance between the rills in the south-western areas represented by the slopes (4, 5 and 6) reached (11.2, 12.5 and 11.6 cm) respectively. These areas are characterized by medium erosion. And what helps to activate the erosion processes in the rills in these areas is the significant increase in the degree of sloping, which ranged between (4.8^{o} - 6.4^{o}).

3. The low depths of the rills formed after rainfall which ranged between (3.1 – 6.2 cm) indicate that there is no continuity of runoff water in those rills for a long time, due to low concentration of rainfall on the slopes.
4. The morphometric characteristics of the lengths and widths of the rills clearly indicate their ability to erode the components of the surfaces; as their average lengths ranged between (127 - 311) cm, and their widths ranged between (2.1 – 8.3) cm.

Table 2. Characteristics of rills formed on the slopes of the valleys after rainfall in the upper basin during the rain storm (11 – 14/12/2013).

Slope Number	**Average density Of Rills / m^2**	**Average width / cm**	**Average length / cm**	**Average depth / cm**	**Average distance between rills / cm**	**Gradient** (o)
1	3.5	7.5	311	6.2	9.8	12.5
2	3.3	8.3	309	5.9	8.7	9
3	3.1	6.4	182	5.3	7.8	7.5
4	2.8	3.2	217	4.5	11.2	5.1
5	2.2	2.1	240	3.1	12.5	4.8
6	2.5	3.5	127	4.7	11.6	6.4
7	2.1	3.1	198	4.7	17	6.5
8	2.5	2.8	247	3.1	11.2	6.5
9	1.7	3.5	213	5.2	19.2	4
010	2.4	2.5	254	4.1	15.2	4.6
Average	2.61	4.29	232.7	4.68	12.4	6.69

4.1.2 The Collapse and Weakness of Slopes:

The collapse of the slopes occurs as a result of the instability of the geotechnical processes, namely: the planer failure of rock formations, the rotational failure of slopes materials, and the fluvial materials slope. These processes act on the development of the morphological shape of the slope to approach the convex shape at the top of the slope and the concave shape at the lower part of the slope.

The rock fall and mass wasting processes are active in the slopes that have a gradient of more than 10° as they constitute 74.4% of the total rock fall and mass wasting. On the other hand, these processes decrease in the slopes that have gradients of less than 10° as they account for 25.6% of the total rock fall and mass wasting (Table 3). This clearly indicates the role of the gradient in destabilizing the sediment on the sides of the slopes, where rock fall and mass wasting are more likely to occur with the increase in the gradient (Braathen, 2004).

Table 3. Frequency distribution of the number of mass wasting and rock fall according to gradient categories in the upper basin of Wadi Al-Qa' during the period (2011 - 2013).

Gradient of the western slopes	Less than 5º	5º - 10º	11º - 15º	More than 16º
Number of mass wasting, rock fall	2	5	8	12
Percentage %	7.4	18.51	29.62	44.45

Mass wasting in the upper basin is associated with the size of rainfall, as the likelihood of mass wasting increases with the increase in rainfall. The instability of the western slopes is also attributed to the presence of geological vulnerability factors. Furthermore, we find that the dominance of limestone within Amman and Wadi Al Seer formations in the upper reaches basins, with its inconsistency and weak texture, accelerates their response to the forces of water erosion.

Faults also contributed to the occurrence of mass wasting on the slopes because of the resulting increase in the density of fissures and joints, and the emergence of steep groves with frequent rock falls. The average density of fissures ranges between (2.1 – 4.2) / m^2 with an average of (2.7) / m^2. Fissures occur as a result of tectonic pressure forces, which in turn are the resultant of folding and faulting processes. They also occur as a result of decompression through stripping the upper layers due to erosion or weathering processes. The morphometric characteristics of these fissures, in terms of depth, height and direction, depend on the quality of the rock, and the pressure forces acting on them. Fissures play a major role in developing the exterior of the slopes and increasing the effectiveness of erosive activities as they work as channels for the leaking water, which in turn, weakens the capability of the rocks to resist different weathering and erosion processes, and activates mass wasting and rock fall.

Figures (A-C5) show the places where mass wasting and rock fall occur on a number of cross-sections of the western slopes in Wadi Al-Qa'. What follows is the analysis of those sections.

The first section (A)

This section is located in the upper reaches of Wadi Al-Qa', 2 km away from the watershed area. The right side is characterized by irregular gradient ranged between (8° - 25°) from the top of the slope toward the stream valley. The left side is characterized by steep gradient which ranged between (25° - 30°). This side has an instable structure which activates mass wasting and rock fall on it. The bottom of the slope is covered by a thin layer of rock debris that has a weak textile. The rock layers in this section consist of cretaceous and marl rocks, and a thin layer of flint; they belong to the formation of Amman (B2). These layers are characterized by lots of fissures and frequent cracks; the stream bed is covered with gravel and sand that in some areas have a thickness of 3.5 m.

he second section (B)

This section is located in the area adjacent to the middle basin where the northern sides of the valley are characterized by their severe steepness which ranges between (18° - 35°). This area is characterized by instable structure which activates rock fall. While in the southern area of the valley, the rocky cliffs rise gradually on both sides. The gradient ranges between (5 ° - 15°). Rain-fed agriculture is practiced on this side, especially olive trees. The Formations in this section consist of splintered flint, limestone, marl and phosphate rocks. The right side is covered by a thin layer of rock debris.

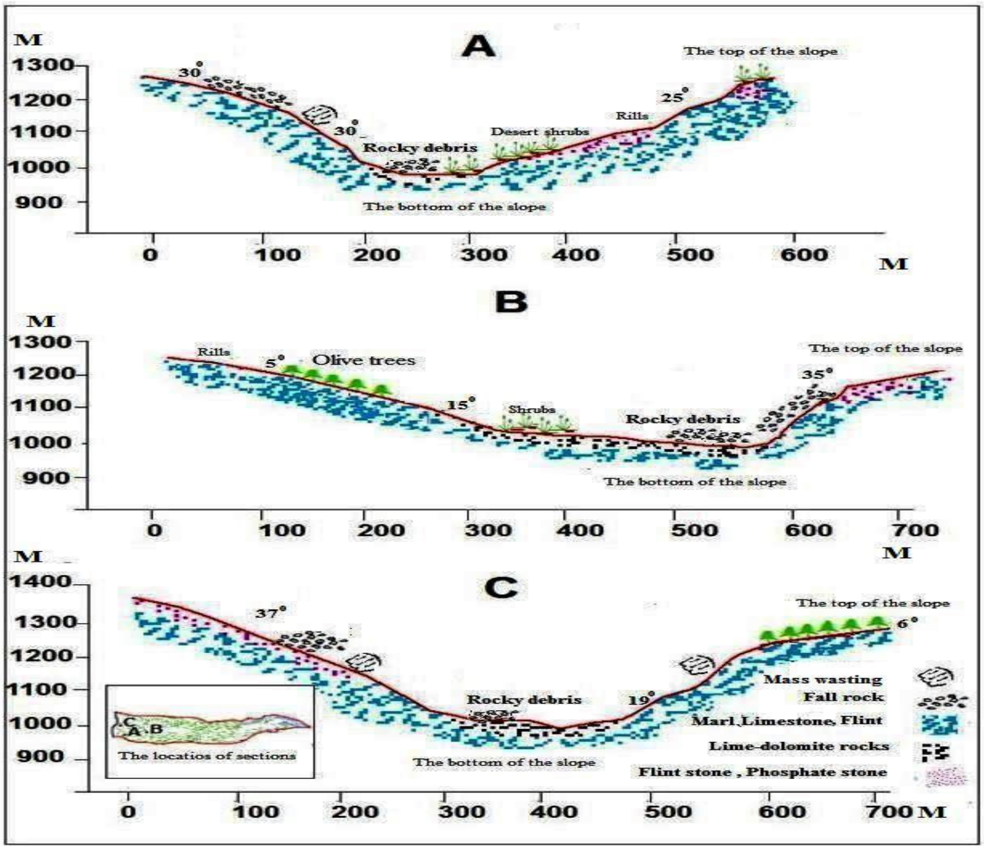

Fig 5. Cross-sections of the western slopes showing the places of mass wasting and rock fall

The third section (C)
This section is located in the area adjacent to the western watershed area of the Valley. The slopes in this area are characterized by their severe steepness and depth as a result of water erosion processes. The gradient in this area ranges between (6 ° - 37°). Mass wasting and rock fall are active on these slopes. The upper part of the slope is covered with a thin layer of soil while the lower part of the slope is covered with jagged incoherent deposits of unstable rock debris. Rocky outcropping only appear near the bottom of the valley, within a height not exceeding 10 m. The rock formations in these slopes belong to the formation of Amman, which consists of successive layers of lime, silica and flint.

4.2. The Morphological Shape of the Western Slopes

The shape characteristics of the western slopes varied form convex, concave to straight. It was found that the upper part of the slope, where erosive forces are minimal, takes the convex shape. Directly below this part, the erosive forces become stronger due to the increase in the volume of runoff water. Sedimentation occurs in the lower parts of the slope which suit the development of the concave shape. It was found that the convex surfaces are more affected by erosion processes than concave and straight surfaces, because of the possibility of the spread of erosion processes over a larger area.

Fieldwork revealed that the concave shape frequently appears in the areas with gradients (6 ° -15 °), it becomes less in the slopes (16 ° -24 °), and it is not found in the steep slopes of more than (30 °); because they constitute sharp grooves. The same goes for the convex shape, it is not found in the slopes of more than (30 °), but it appears heavily in the slopes of (4 ° -15 °). As for the lengths of the slopes, they vary according to the lengths of the valleys, the roughness of the surface of the slope, and their vulnerability to the morphodynamic processes that occur on the erosion slopes. The lengths of the western slopes range between (250-1500 m). The erosion slopes usually end with bottom sediments. They have a gradient that ranges between (3 ° -6 °). Their surfaces are covered with gravel deposits and boulders; the coverage ratio ranges between (10-90%). They often take the straight form, and they are of sedimentary origin.

The western slopes are considered to be the most vulnerable ground units to environmental degradation, due to lack of stability of their surface sediments as a result of the activity of morphodynamic processes.

5. Conclusions:

The erosion slopes spread adjacent to the upper reaches flowing into Wadi Al-Qa'. They spread in different directions according to the headwaters of the western valleys flowing in Wadi Al-Qa'. These slopes vary in terms of their morphological characteristics according to their evolution and development; and their vulnerability to the basin changes imposed by geo-morphodynamic processes prevailing in the upper basin of the Valley. The most important of which are water shearing force which the western slopes are subjected to during rainy periods, as well as being subjected to tectonic movements resulting in collapse of lateral slopes of valley.

The sloping characteristics of the western slopes of Wadi Al-Qa' vary in terms of their gradient, their length and their shape. The gradient increases as we head west; due to the vertical and lateral erosion processes that make the valleys deeper and deeper, as well as the mass wasting and rock fall on these slopes. The cross-section of the erosion slopes takes different shapes, that is, the straight shape, the concave shape, and the convex shape.

The morphological shape of the western slopes is considered a direct product of several overlapping basin variables; the most important of which is the magnitude of water erosion forces acting on the components of the slope surface, and the stability of the rocky structure of the slope. The study also shows the role of the slope shape in determining its morphological characteristics. It was found that the convex surfaces are more affected by erosion processes than concave and straight surfaces, because of the possibility of the spread of erosion processes over a larger area. The study also shows the role of the gradient in development of slopes morphology as rock fall and mass wasting processes are more active in the slopes that have a gradient of more than 10° as they constitute 74.4% of the total rock fall and mass wasting.

The study revealed the role of the rills as a geomorphological factor in developing the slopes through trenching the slopes surface and eroding the surface ingredients. The effectiveness of the rills increases with the increase in their converging degree, and the increase in their morphometric dimensions as we approach the northwest areas in the upper stream.

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