

GEMORPHOLOGICAL STRUCTURE OF LANDFORM CHARACTERISTICS AS A REFERENCE FOR DEVELOPMENT RECOMMENDATIONS IN WADI RUM PROTECTED AREA

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Abstract: This research will look at numerous fundamental geomorphology ideas, with a focus on geomorphological systems. Geomorphology researchers use a variety of landscape evolution models, with the assumption that unstable landscape equilibria evolve quickly. We investigate the relationship between geomorphological concepts and ecosystem dynamics, with a particular focus on categorizing plant groups based on various landform features observed in southern Jordan. By conducting research in this region, we aim to gain a deeper understanding of previous scholarly discussions surrounding Wadi Rum, specifically in the context of geomorphology. Furthermore, we must integrate geomorphological references with socioeconomic research, given their inextricable link to community activities and development. This research used a geomorphological technique to thoroughly examine and assess the physical and ecological attributes of the Wadi Rum Protected Area. The research used both qualitative and quantitative methodologies to provide a thorough understanding of the geomorphological structures and processes affecting the area. The researchers performed a comprehensive content analysis of current scientific literature, concentrating on geomorphological characteristics and their interaction with ecosystems. This study established a theoretical framework and criteria for articulating field observations, providing insights into the degree and scale of temporal change. The diverse geomorphological features play important roles in shaping and influencing local ecosystems. According to established theories, the unique characteristics of landforms offer valuable insights, as they emerge from a lengthy process of morphogenesis, or landscape evolution. This makes them ideal for analysis when formulating recommendations for sustainable development, which considers the unique qualities of landforms. The researchers utilized Global Mapper and AutoCAD for geospatial data analysis, digital terrain modeling, and accurate topographic mapping, aiding geomorphological analysis and sustainable development planning. We should avoid uncontrolled and unsustainable development to preserve the area's landform characteristics for future generation.

Keywords: Wadi Rum Protected Area (WRPA), geomorphological structure, landforms, geomorphology on ecosystems

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INTRODUCTION

Wadi Rum Protected Area (WRPA) holds immense significance in terms of its rich history, not solely due to its unique culture and the notable sites found within it, but also because of the breathtaking landscape and diverse biodiversity it diligently protects. The rugged terrain of this region provides an ideal refuge for a wide variety of wildlife and their respective habitats, creating a critical sanctuary for nature. The landscape, preserved predominantly in its natural state, presents a mesmerizing sight that draws tourists from populated countries who are eager to witness its stunning beauty.

Although the area appears relatively barren at first glance, it is home to native and specialized flora, which plays a vital role in grazing practices for local livestock. A small population resides in the vicinity of the protected area, relying on it not only for livestock grazing but also for its picturesque landscapes and rich historical value, further emphasizing the area's importance in both agricultural and cultural contexts. WRPA has transformed into an appealing hub for the exchange of experiences and the dissemination of knowledge, thanks in part to its various activities that encompass creative writing, photography, painting, sculpture, and film-making. The high quality of geomorphological studies conducted in this region

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provides invaluable insights, paving the way for significant advancements in managing human impact on geosystems. This ongoing research is critical in the efforts to substantially reduce the anthropogenic pressures within mostly protected areas. Consequently, the primary aim of our study was to develop relevant landform characteristics using Wadi Rum and Ma'an as a foundation for potential development recommendations. This development primarily concerns the establishment of a desert park, which would be characterized by various forms of infrastructure enhancement and diverse industrial and investment opportunities. In order to mitigate potential conflicts with the nearby WRPA, it is essential to manage the area thoughtfully, taking into consideration the distinct geodiversity that these developments will generate.

The key factor in advocating for the appropriate development of the region lies in accurately determining the landform-related geomorphological dynamics, wherein the applicable planning principles must be instituted. The entirety of the work comprises four substantive chapters. The geographical conditions present in the WRPA and its surroundings play a crucial role in influencing the geomorphological dynamics of the existing eco geosystems. We have also established a comprehensive group of geo components and geo processes that most effectively reflect the intricate relationship between the geomorphology and the ecosystems present in the area. In conclusion, we delve into the intricacies of the geomorphological structure associated with selected landform characteristics. Based upon the outcomes of our analyses, we engage in a discussion surrounding the existing knowledge concerning the geomorphological typology of the region and identify potential areas for future research that could reinforce the recommendations for the area's development plans.

To minimize conflicts with the conservation objectives dedicated to the Wadi Rum Protected Area, we propose diverse potential themes closely linked with the new desert park. The landform characteristics inherent to the area may serve as a solid foundation for future development opportunities within both the tourism and facilities sectors. This development will be mindful of the principles of sustainable growth, the unique natural experience of the place, and the existing character that defines the Wadi Rum reserve, ensuring a harmonious relationship between development and conservation efforts (Gani et al., 2024; Al-Shawabkeh, 2023; Wright et al., 2023; McPherran, 2023; Rowley et al., 2021).

2. BACKGROUND OF WADI RUM PROTECTED AREA

The geography of Jordan is uniquely characterized by a richness of several iconic landscapes that attract the steadfast attention of both locals and foreigners alike. These remarkable and special natural areas require ongoing preservation, enhancement, and restoration efforts in response to the ongoing environmental degradation threatening their existence, in order to secure long-term benefits for future generations. Consequently, seven distinct natural areas in Jordan have been officially declared as protected areas to safeguard their integrity. One of the most recent natural areas to be designated as a protected area is the renowned Wadi Rum Protected Area, which was designated in 2011. This stunning Wadi Rum Protected Area is strategically located in the southern part of Jordan and is included in the protected area category V, which is classified as a protected landscape or seascape. This classification emphasizes the importance of conserving its unique landscape while allowing for sustainable tourism and local use (Jawabreh et al., 2024a; Shatnawi & Obaidat, 2022).

Wadi Rum is a deep, dry valley nestled on the edge of southern Jordan. Wadi Rum, roughly half the size of Amman, is located 60 kilometers east of the Jordanian coastal city of Aqaba and about 100 kilometers south of the ancient Nabatean ruins at Petra. Sandstone and granite peaks, worn over millennia by an unyielding desert wind, surround the valley. The highest of these mountains reaches 1,754 meters above sea level. Large sand dunes scatter the ancient valley floor, interspersed with a series of granite and basalt hills arranged along a north-south axis. In the east, Wadi Rum gives way to some 720 square kilometers of emptiness, a flat and featureless desert plain that stretches all the way to the border with Saudi Arabia. Wadi Rum Protected Area lies on the east bank of the Jordan Rift Valley, with an elevation of 900–1754 m above sea level. In the southern part of the area, Wadi Rum Protected Area meets with Shaumari Wildlife Reserve.

It is an area that covers 589.285 km², and the planned expansion of the area will be about 1500 km². The only residents are about 29,000 local Bedouin herdsman, and about 4,000 of the local people belong to the Assyrian minority. The word 'Rum' is derived from an Aramaic word meaning elevated and high, which is appreciated in relation to its dramatic cliffs and landscape. The area includes a variety of stone, sand, and rock terrains. The Umm Ishreen peak is the highest mountain in the area, with an elevation of 1754 m above sea level. A small portion of the area, 29.69 km², annually receives precipitation of 25–50 mm. Furthermore, Wadi Rum is known for its well-preserved petroglyphs, inscriptions, and archaeological sites, which can be dated to the Nabataean, Islamic, and pre-Islamic periods. Given the integrity between nature, humans, and place, the cultural and natural wealth in the area were added to the World Heritage List. The total length of the designated boundaries of Wadi Rum Protected Area is about 550 km as shown in Figure 1.

The landscape encompasses the various combinations found on Earth's surface. The diversity of landforms and relief is shaped by a trio of fundamental aspects, namely altitude, slope, and shape, all of which arise from a multitude of processes. Within the realm of geomorphology, it is well-recognized that the various landforms and the relief they represent are outcomes of both endogenous processes, those that originate from within the Earth- and exogeneity processes, or those that stem from external forces. A variety of morphogenetic processes contribute to this complexity, including but not limited to erosion, weathering, deposition, and accumulation, along with significant tectonic activity. This study will engage with several foundational theories of geomorphology, with particular emphasis on geomorphological systems.

Researchers in the geomorphology field also draw upon various landscape evolution models, with the understanding that unstable landscape equilibria are evolving at a rapid pace. The interconnectedness between geomorphological concepts and ecosystem dynamics is explored, especially as it relates to the classification of vegetation communities that are based on distinct landform characteristics found in southern Jordan. By delving into research within this study area, we aim to deepen our comprehension of prior academic arguments concerning Wadi Rum, specifically within the

context of geomorphology. Furthermore, it is crucial to integrate geomorphological references with socio-economic studies, as these are deeply intertwined with community activities and development.



Figure 1. Wadi Rum Protected Area Map (Source: Prepared by the researchers, using Global Mapper software)

The various geomorphological aspects serve as essential influences that shape and affect local ecosystems. In alignment with established theories, the distinct characteristics of landforms offer valuable insights, as these landforms emerge from a protracted process of morphogenesis - essentially, landscape evolution - which renders them optimal for analysis when formulating recommendations for sustainable development, wherein the unique qualities of landforms are duly considered. Moreover, geomorphological orientation is rooted in the theory of soft systems, which posits that development is synonymous with accelerated advancement, frequently assessed through an economic lens.

The field of geomorphology examines systems complete with their specific boundaries and components, wherein we can identify two principal components at play: the abiotic non-living elements, which encompass the array of landforms, and the biotic component, which comprises the diverse ecosystems that thrive within this geomorphological context. (Bouma et al., 2022; Morino et al., 2022; Gkoltsiou & Mougiakou, 2021; Górska-Zabielska et al., 2024). Geomorphology is often defined as the study of the processes that create and develop the Earth's surface forms and the forms themselves. It is linked with a variety of subjects and techniques that educate people about Earth systems, such as geography, geology, pedogeography, and ecology. In more detail, geomorphology investigates landform changes generated by the gradual or sudden impact of geomorphic forces, namely weathering and erosion. More broadly, geomorphology is an interdisciplinary science concerned with relationships between the Earth's surface and ecological systems. It is a "place-based science" closely related to "earth surface processes and ecological patterns and processes in natural habitats." Geomorphology involves a number of special disciplines, including process geomorphology, which studies the working conditions and mechanisms of geomorphic forces according to the great and medium physical laws, and the analysis of landforms based on the landforms that have been and are still being created by geomorphic forces (Al Dein, 2021). Research on landform characteristics includes landform interpretation and the correlation between human activities and ecological impacts.

Moon Valley, the northern expanse of the Wadi Rum Protected Area, is a popular stopping-off point for tourists visiting the desert. Its cliffs, mountains, and rugged hills present a variety of colors and shapes, making it one of the most popular stopping-off points for visitors. The eastern boundary of Moon Valley is marked by dramatic sand dunes, while its western border abuts the large gray and dark red colored rock table of Umm Ishrin, a remnant of a massive volcanic outflow. To the north of the upper valleys is the fantastic canyon of Barrah Siq, which has a long south-north orientation, making it suitable for developing later. This decrease in speed by 30 times of seasonal water runoff affects settlers who depend on it to prevent flooding their crops. The top of the wadi from which the waters of the Siq derive is called Hiz Risheh, Figure 2.

One of the key features of the Wadi Rum Protected Area is Mushroom Rock, located more than 150 meters away from the southern entrance to Wadi Rum village. Mushroom Rock is a unique granite rock formation in the desert of Wadi Rum, formed through geological processes like physical and chemical weathering and abrasion over millions of years. It stands without a sibling, contributing to the splendour of the natural environment and making it an educational tool for geology and natural history. Barrah Siq is considered one of the most interesting places in Wadi Rum due to its narrowness, rock walls rising for well over 100 meters, and holding a variety of animals and plants that can live in an apparently unusual

environment. Visitors can enjoy the tremendous sound of water rushing, echoing healing sounds, mist, and surprises around every corner. In addition to the natural attractions of Barrah Siq, there is a station for one of the tours every day of the mid-season taking place at one of the junctions. The Siq starts about five hundred meters east of the rock, to which a desert road leads, Figure 2. Barrah Siq runs for nine kilometres, and guests stay and learn about the customs, eat together, participate in the music, receive stories of the Bedouin customs and lifestyle, and maybe watch the preparation of the Zarb, a Bedouin barbecue. Many guides are qualified chefs and provide accompanying services.

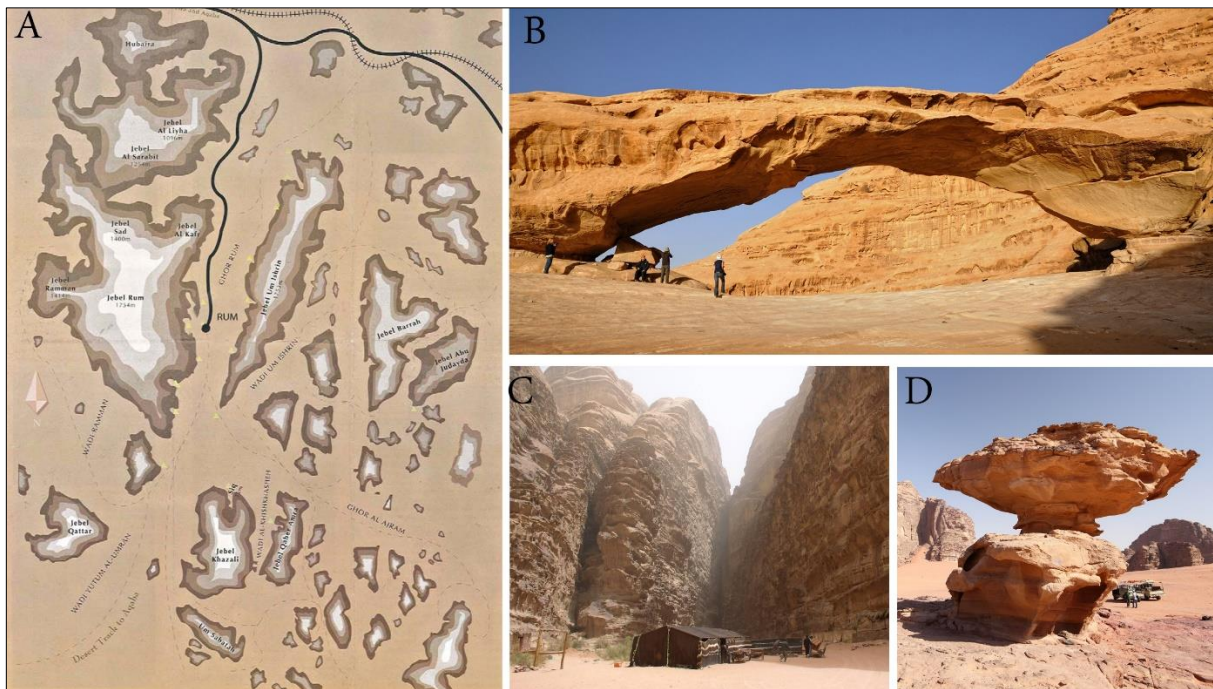


Figure 2. A: Topography of Wadi Rum Protected Area (Source: Authors prepared by the researchers using Global Mapper software) B: Moon Valley C: Barrah Siq; alongside a Bedouin camp D: Mushroom Rock (Source: Authors, April 2024)

Geomorphological research can clarify two basic aspects of landform characteristics in Wadi Rum: the first being the natural, original characteristics, and the second, the various graded characteristics that have developed in the course of the relevant interactive relations. Research into the scope of geomorphology is relevant to solving the interdisciplinary approach of environmental planning, which studies geomorphological aspects concerning recommendations for managing Wadi Rum as an example case. Given these definitions and the cultural and historic context of the research area of geographic and landscape approaches, the geomorphological definition will be discussed as a starting point. The geomorphological scientific tools will be directed toward the creation and development of Wadi Rum's physical spatial characteristics, applied in the few sketchily interdisciplinary studies, not presenting a viewpoint as its primary objective.

METHODOLOGY

The geomorphological approach in this study was designed to systematically investigate and analyze the physical and natural characteristics of the Wadi Rum Protected Area. The methodology relied on a combination of qualitative and quantitative techniques to provide a comprehensive understanding of the geomorphological structures and processes influencing the region. The researchers conducted an extensive content analysis of existing scientific literature, focusing on geomorphological features and their interaction with ecosystems. This review provided a theoretical foundation and guidelines for presenting characteristics observed in the field, offering insights into the extent and magnitude of change over time. Fieldwork played a pivotal role in this study, involving detailed surveys to collect qualitative and quantitative data on geomorphological landform changes. The researchers employed Global Mapper and AutoCAD as essential tools for analyzing geospatial data, creating digital terrain models (DTMs), and producing accurate topographic maps. These technologies facilitated the visualization and analysis of landform characteristics, supporting the interpretation of geomorphological processes and the impacts of natural and human activities.

The data collection process involved two main techniques: a comprehensive literature review to establish a foundational understanding of the site, and the application of semi-quantitative and quantitative tools to represent observable phenomena. These processes were documented using texts, images, and illustrative graphics, with the field data analyzed using digital techniques, including Digital Terrain Models (DTMs) processed in Global Mapper and detailed design schematics developed in AutoCAD. The integration of qualitative engineering geology and ground form analysis provided a deeper understanding of the processes shaping the region. These were the established-in-field or field-based methodologies. An interdisciplinary approach was also supported. Yet, as views capes are established through locally deposited sediments, and their concretion and the composition and facies of the geological materials are primarily responsible for their characteristic formation, the majority of interpreted landform characteristics are derived

from a combination of qualitative and field-based techniques involving an understanding of qualitative engineering geology and ground form analysis, with the key lens of identifying features and processes.

Such recommendations are directly relatable to Wadi Rum, as detailed, in-depth geomorphic investigations are only justified and required in response to major energy resource, geological and landform changes, and general overarching increases in visitation, as are found in common where archaeological evaluation investigations are indicated.

CASE STUDY

Case Study Wadi Rum is an incredibly unique and remarkable area, specifically designated for extensive and detailed geomorphological investigation. It is widely recognized as the largest wadi basin throughout the entire region of Jordan, encompassing extensive superficial alluvial deposits that cover a substantial area of approximately 750 km², making it a significant geographical feature. The surrounding mountains that beautifully frame this wadi are predominantly composed of durable calcareous rock as well as striking and visually captivating sandstone formations, which contribute to the area's distinctive appearance. Wadi Rum is notable for not only its intriguing geological features but also for its unique physical and ecological diversities that set it apart from other regions across the globe.

The elevations within this extraordinary area vary significantly, ranging from 901 meters below sea level to an impressive 1754 meters above sea level, showcasing the dramatic topography of the region. The annual average temperature experienced here is generally warm, fluctuating within a range of around 5 to 22 degrees Celsius, with the warmer summer months stretching from April to September, and the cooler autumn months from October to March presenting more moderate conditions. Additionally, the yearly precipitation recorded in this fascinating study area averages a relatively low 33 mm, clearly reflecting the arid conditions that prevail throughout this remarkable landscape. The area serves as a vital habitat for numerous unique flora and fauna species, which include notable plants like Weinman Nia and Cupressus, as well as the endemic mountain goat, which has adapted to thrive in this environment. Notably, herds of these amazing goats have been grazing in this picturesque area since as far back as 1917, illustrating the long-standing relationship between the species and their habitat. The study area's climate is distinctly characterized by a hyper-arid Mediterranean classification and is categorized under the broader desert climate according to the comprehensive Köppen-Geiger climate classification system, further underlining the unique environmental conditions present in Wadi Rum (Obeidat et al., 2021; AlZidaneen et al., 2023; Al Dein, 2022; Allan & Ludwikowska-Kędzia, 2023; Amireh, 2020; Hseinat et al., 2023).

Physical Characteristics

The physical characteristics of the study area illustrate a varied and dynamic landscape. In particular, rocky outcrops and altiplanos are a defining feature in archaeological regions such as the Baz' plateau, which extends both to the east and west of the valley. The highest elevation within this region is dominated by Jebel Rum, a majestic peak whose composition primarily consists of granite, gneiss, and schist. Notably, this area has been a site for the extraction of iron from magnetite minerals, a practice that has been carried out since the onset of the Islamic period, thus adding historical significance to the local geology. The wadi bed itself is generally flat and is covered with a diverse range of sediments, which contribute to the unique physical landscape of Wadi Rum.

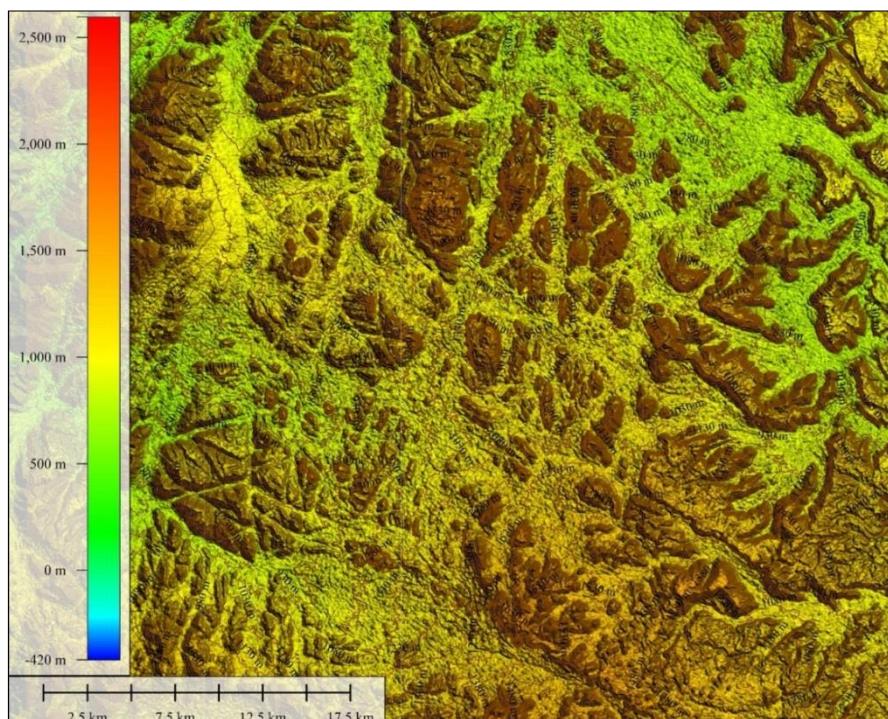


Figure 3. Contour and Landform Analysis Map for Protected Area of Wadi Rum Geomorphology (Source: Author, prepared by the researchers using Global Mapper software)

These characteristics, including the relatively low slope and the specific composition of the bed, facilitate a continuous and interconnected wadi system. Moreover, these features have remained largely untouched by agricultural practices from 5470 BP up to the present day. This lack of agricultural interference has allowed Wadi Rum to maintain its distinctive geomorphological characteristics, which can be classified as a dominant typology for overland and soil geomorphologic features. Furthermore, the geomorpho-depositional traits observed in Wadi Rum contrast sharply with those found in other, more traditional gullies and deeper basins that have been formed through tectonic or structural processes as it clear in Figure 3.

The average rate of wadi development has been measured at approximately 1.36 meters per annum in al-Qara, while Wadi Aghdera shows a more rapid average development, reaching around 3.6 meters per annum since the year 2014. These measurements highlight the dynamic nature of the environment in Wadi Rum and underscore the relevance of ongoing geological processes within this remarkable area (Sen et al., 2023; Mateciucová et al., 2020; Jawabreh et al., 2023).

RESULTS AND DISCUSSION

The geological evolution of Wadi Rum is a climatic process extending over millions of years. Different sequences of deposition, concurrence, compaction, and lithification of a variety of rock units have influenced the characteristics of the land. In comparison to the different volcanic materials, the three sedimentation units played a dominant role in shaping the land. They are influenced as well by geological processes such as tectonic movements, sedimentation, and erosion. The Wadi Rum depression has experienced a multitude of geological and geomorphological changes since the Triassic period. The uplift of some important geological structures, such as the Sarhan anticline, as well as the injection of molten rocks from the earth's mantle inside the whole region, has been the result of movements on a tectonic scale. Thiophyllite is the principal rock type present across Wadi Rum. Many chemical cycles of formation, erosion, and deposition have influenced the land to give the region an articulate character. The climate lowers or increases the degree of chemical etching and the presence of different creatures over long geological periods, knitting a complex story into the fabric of the land.

The lake deposits, groundwater, climate, and river variation are explained with a chronological framework. The reactivation of chemicals is explained in recent times as well. The geological story tells why and how the curves, slender canyons, curving depressions, and the different rock layers in Wadi Rum look as they do today. The character of this geological process is the dominant factor in shaping the desert ecosystems and varied habitats in Wadi Rum Protected Area, as well as an indicator of where to ban any future development lands. The topic aims to describe the geological setting of Wadi Rum and offers an outline of the development over the many geological periods. It starts by giving an overview of the geological evolution of the Middle East, the Levant, and the Wadi Rum region.

Geological events are discussed in terms of sedimentation and volcanism, and subsequent tectonic activity. This led to the formation of anticlines and synclines in the development stage of Wadi Rum around 20 million years ago. In the final stage of Wadi Rum as we see it today, the last model deals with lava flows and active water action that shaped the land surface. Recent processes are also discussed in terms of the dominant forces in the period around the falls and the reactivation of the faults around Wadi Rum. The relation between the geological processes and climatic changes is included in the notebook. This integration serves to give an idea about the geological foundations that shape the characteristics of the land surface today. This expanded value requires more work and inquiries to be verified. This content aims to give a clear understanding of the thesis goals and the capabilities of the authors.

During the past 30 million years, Arabia and associated African plates have been colliding. In the process, the Red Sea has opened up, making Jordan located at a convergent plate boundary. Along the eastern arm of the Red Sea, there is evidence for hundreds of dyke intrusions and effusive eruptions from at least 30 million years ago until just a few million years ago. UV-contaminated quartz grains from igneous granite crystals are near shoreline sandstones more than 27 million years old. The volcanic rocks include rhyolites, basalts, dolerites, and other magma types. The study area is essentially the profoundly eroded roots of the southward Intracontinental Extensional Axis.

The rocks themselves encompass fluvial sandstones, pedogenically developed soils, and alluvial gravels and conglomerates resulting from denudation occurring in sub-pluvial punctuated periglacial environments over the last 500,000 years. There has been a long time scale (i.e., millions of years long) association between the onset of uplift in western Jordan and rapid downcutting in the paleolandscape of the study area, resulting in a stacked sequence of 21 base-level surfaces in the present-day landforms from above Wadi Rum more or less southward to Wadi Al Hassa on the Saudi Arabian border. Three interwoven elements of fluvial terraces sit above quasi-sediment-free paleolands where post-exposure and heavy weathering have thoroughly modified many of the rock masses, so that original periglacial landforms are difficult to interpret. Given we have spent a lot of space on the past, we shall capitalize on staying with it, but moving to today.

As a result of geological processes and climates, the landforms of Earth vary from one place to another. The uniqueness of each area contains differences in their landforms, landform characteristics, and processes; Wadi Rum comprises its part. The physical characteristics of Wadi Rum can be seen from its landforms. First, the cliffs of Wadi Rum are the most well-known landform in the study area. The landforms are made of sedimentary rocks such as sandstone and limestone from different geological ages. The layers of the sedimentary rocks are characterized by different color shades, depending on the amount of different mineral compositions within the layers. The structures of the landforms are being carved by continuous erosion and remain as an ecosystem of their structures. A valley or numerous valleys with different dimensions is another landform in Wadi Rum. Valleys are being sculpted within the massive plateau rock. Then, the valley is sculpturally reshaped while being influenced by climate. The sculptural shaping of the valley is very unique, and this is most well-known. The next one is Jabal. It consists of sedimentary sandstone and limestone hills that have been sculpturally shaped in a particular way. The uniqueness of this configuration makes it a place of tourism interest. Arches, rare natural stone

formations, are spread in the inner plains and the peripheries of mountains. The characteristics of landforms being classified into some names help for more localized understanding and detailed conservation and development issues. Wadi Rum Valley is one of the globally protected areas that face tourism pressure. To support resource conservation and, at the same time, to address the challenges of developing the area, a meeting of a development-indicator study would be carried out. According to location classification in the physiographic unit of Wadi Rum Valley, we identify unique limestone and marble hill landforms in the northeastern foot of Jabal Khash first, and then the monadnock system, inselberg, wave rock, monumental chamber, and sandstone mountain with granite pinnacle are common in the low-height sandstone plateau that is marked as central physiographic units of Wadi Rum Valley, and they spread everywhere.

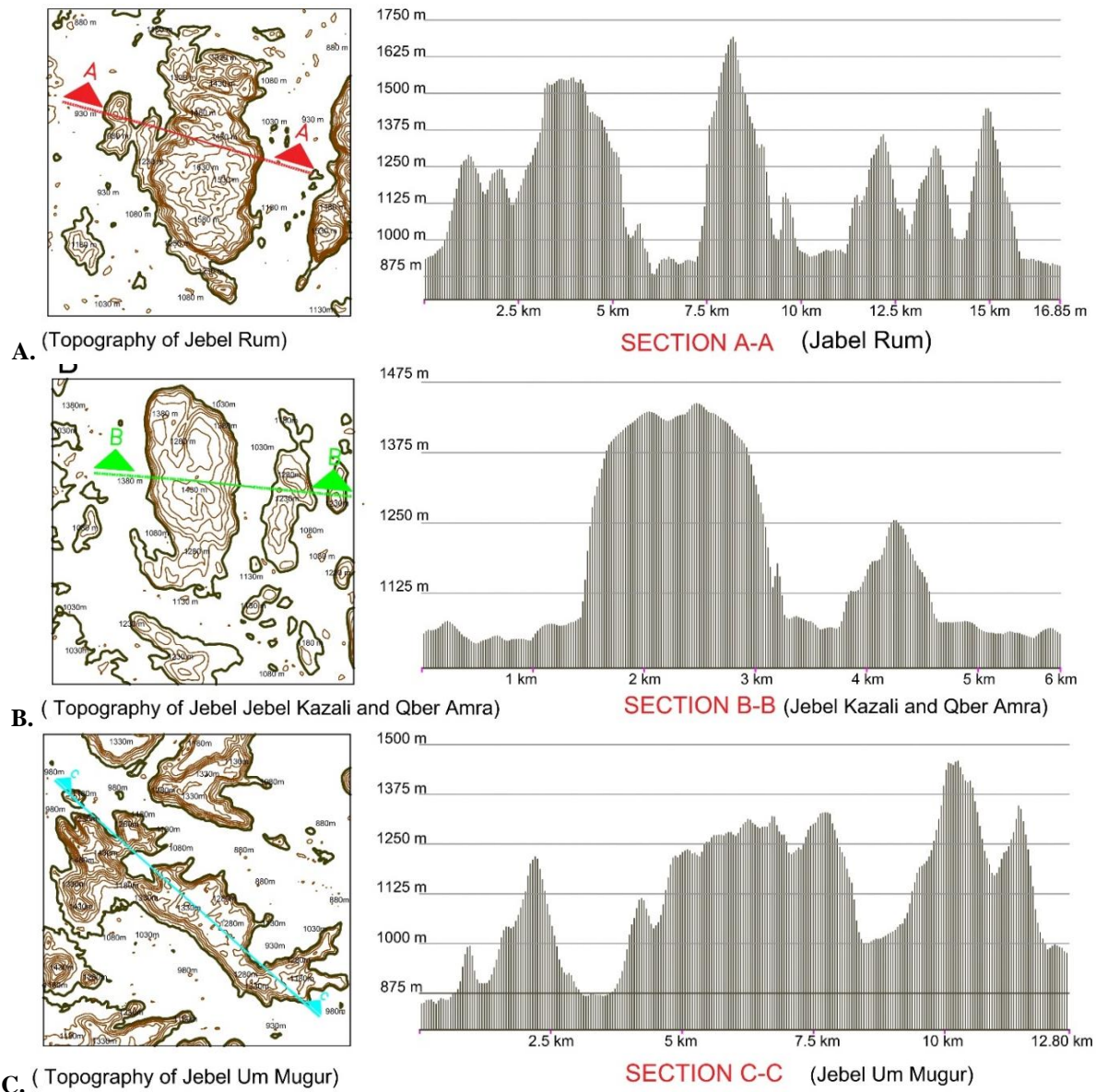


Figure 4. Geomorphological Terrain Map of Wadi Rum represents some of the main landforms such as mountains, valleys, A: Path and Topographic Contour Map of Jebel Rum B: A: Path and Topographic Contour Map of Jebel Khazali and Qber Amra C: Path and Topographic Contour Map of Jebel Um Muger. Source: Author, prepared by the researchers using Global Mapper software

At the region, we capture a flat low rocky plain approximately 50 m in length at the eastern part of Marra Ebdayyih. Many marls are spread on the western side. The scale of side and bottom heavy edges that dominate minor marls in the site relates to abnormal weathering of sands that are applied as terracotta’s protector.

Contour lines also draw attention to the interpretation of elevation modification. You can determine the contour interval, or contour spacing, between two or several contour lines at the bottom or side of a mapping grid. It measures the distance between two consecutive contour lines. It visually indicates hills or taller mountains and flat land areas. As the spacing gets larger, it draws attention to the increasing elevation change. However, the close proximity of spacing refers to a gentler or lower elevation change. It refers to the relative depth of depressions. A closed contour line informs about hills where a range of high to low elevation occurs. In contrast, a closed contour line can show depressions or valleys. These mapping grids use information systems to reveal surprises, land value, and contour usage, attracting the attention of geological and environmental planners. Other topographic maps also use the same grid system, which

interprets the shape of the earth's landscape indicated by closed contour line symbols. Even though they only scratch the surface, circulating trends of land and depressions are very useful for verifying discoveries in the field of Geomorphotectonics. The geomorphology of Wadi Rum is based on topographic contour maps of Jebel Rum, Jebel Khazali, and Jebel Um Mugur as shown in Figure 4. The chosen region, Wadi Rum, lies 35 kilometres southeast of Petra, with the Wadi Rum visitor center serving as the main vista site. Known for its role in filming *Lawrence of Arabia*, Wadi Rum is a cinematographic site. The research questions are: "How does the Wadi Rum bedrock's spatial formulation differ from that of the Jebel Rum, Jebel Khazali, and Jebel Um Mugur mountain bedrocks?"

The primary responsibilities of the managers overseeing the remarkable protected areas encompass both the safeguarding and showcasing of the stunning examples of breathtaking landscapes found within these regions. A deep understanding of the diverse landscapes present in Wadi Rum can be significantly enhanced by systematically organizing the simpler landform characteristics into various categories of landform groupings or classifications. These landforms possess distinct properties that have drawn the interest of geomorphologists, leading them to explore potential specific subclasses. Numerous attempts have been made to classify landforms, starting with those classifications solely focused on form. The work of geomorphologists and their followers has contributed to this field, evolving into systems that are based on the developmental processes that shape surface characteristics, influencing how these landforms are perceived, either in totality or in part. Topographic cross-sectional elevation analysis of Wadi Rum Protected Area was made over the entire area covering 90 km to give us landforms possess distinct properties that shape surface characteristics, Figure 5. Such classifications not only aid in understanding the unique features of these landscapes but also play a critical role in the thoughtful management of the natural heritage found in protected areas.

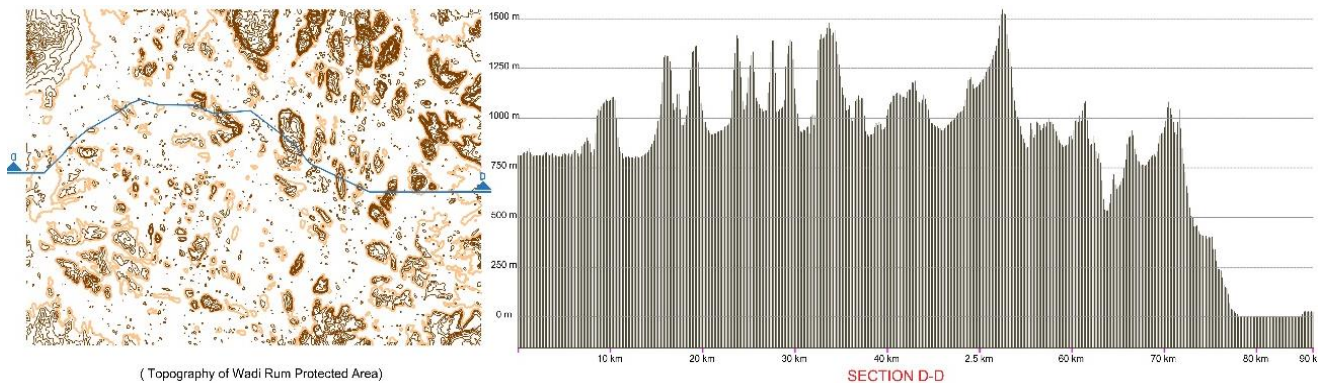


Figure 5. Topographic Cross-Sectional Elevation Analysis of Wadi Rum Protected Area (90 km)
(Source: Author, prepared by the researchers using Global Mapper software)

Some previous classifications of landform are somewhat negative in nature; that is to say, they primarily address the absence of specific influential factors, such as eolian processes or the simplistic design of unitary valley floors, which can be shaped or modified by impactful elements such as the movement of running water. When we take a closer look at this subject, it becomes evident that any given landform is highlighted and stands out distinctly from the conditions categorized as 'non-eolian' or from the state characterized by the absence of any igneous activity. The classification of landforms plays a crucial role in enhancing our understanding of various ecological zones and their micro-zones, which possess unique conservation statuses that can be recognized as important on universal, regional, or purely national levels.

This systemic approach towards landform classification has also led to insightful suggestions regarding which landforms serve as essential cultural heritage niches and corridors, and furthermore, which locations hold a significant degree of personal spirituality and are of religious importance to various communities. It is important to recognize that diverse landforms carry varying biodiversity potentials as well as differing degrees of habitat significance, contributing to their subsidiary roles in the broader context of habitat distribution. Approximately 20 years ago, scholars divided opportunity surface characteristics into multiple categories, which included concepts focusing on subtle undulations, sharp and narrow ridges, and valleys, along with distinctive elongated landforms that are typically found just above the emerging ridges and valleys of the landscape (Zhang et al., 2021; Lin et al., 2022; Wang et al., 2023).

1. Impact of geomorphology on ecosystems and biodiversity

Within the extra-dry extreme desert environment of Wadi Rum, the intricate geomorphological features of various landforms have a substantial and direct impact on the ecosystems present in this unique setting and, subsequently, Wadi Rum's remarkable biodiversity. This relationship is evident through the specific wetness needs of dominant infrastructural materials that significantly influence the creation and development of different soil types, as well as the overall availability and distribution of vital rainwater and moisturized rock surfaces throughout the region. These interconnected factors work together to create the diverse habitats that ultimately define the conditions necessary for various flora and fauna communities to thrive. Additionally, the distinct rock savannah of the sandy gravel plains serves as yet another compelling example of a geological structure that leaves a lasting signature mark on the ecosystem dynamics found within Wadi Rum. The fineness and composition of the bedrock that comprises the desert pavement, along with the amount of soil cover that has been deposited on this pavement over time, play critical roles in

determining the plant communities that can establish themselves in this arid environment, as well as the soil microbial activity present within the upper 30 cm of soil just below the surface. The array of natural habitats that are found within the different types of landscapes in Wadi Rum is widely considered to be an important link that connects geomorphology, biophysical research, and the rich variety of ecological communities that depend on these conditions. (Jawabreh et al., 2024b; Albalawneh et al., 2022; Al-Halbouni et al., 2022; Awadh, 2023).

Former works carried out within the art of geomorphology discussed the details of geomorphological mapping, analysis, and classification of the landform characteristics of Wadi Rum. However, these materials lack the ecological link between the physical environment and the biological communities. Generally speaking, geomorphological integrity should be preserved or affected to the least possible degree to maintain the halophytic communities as well as the existing animal populations and their abiotic and biotic spheres. Any change in the integrity of this structure may individually or collectively carry negative implications according to the sensitivity and adaptability of the site biota and the speed of post-disturbance ecological reorganization. This is in addition to other possible changes in sediment retention and water percolation that are directly related to water table movement. Geomorphological effects on ecological distribution could generally be noticed via changes in ecological equilibrium due to geomorphological-based changes in microclimate and consequently respective vegetation. Several attempts have been made to assess the relationship between intensities of human activities, the carrying capacity, and vulnerability of geomorphological features (Al Fahmawee & Jawabreh, 2022a). Observations using Digital Terrain Model (DTM) for Geomorphological Study of Wadi Rum in north Wadi Rum as it appear in Figure. 6, suggest that some of the most sensitive and easily visible landform features have a history of active use by local people for hundreds, if not thousands, of years. Landscapes in this area exhibited both natural and cultural processes and concluded that many of the most striking geomorphological features of the area have been modified by long-term human activity. Although the extent of this modification is still the focus of ongoing research, preliminary results emphasize the importance of collaborative and informed decisions about park resource use .

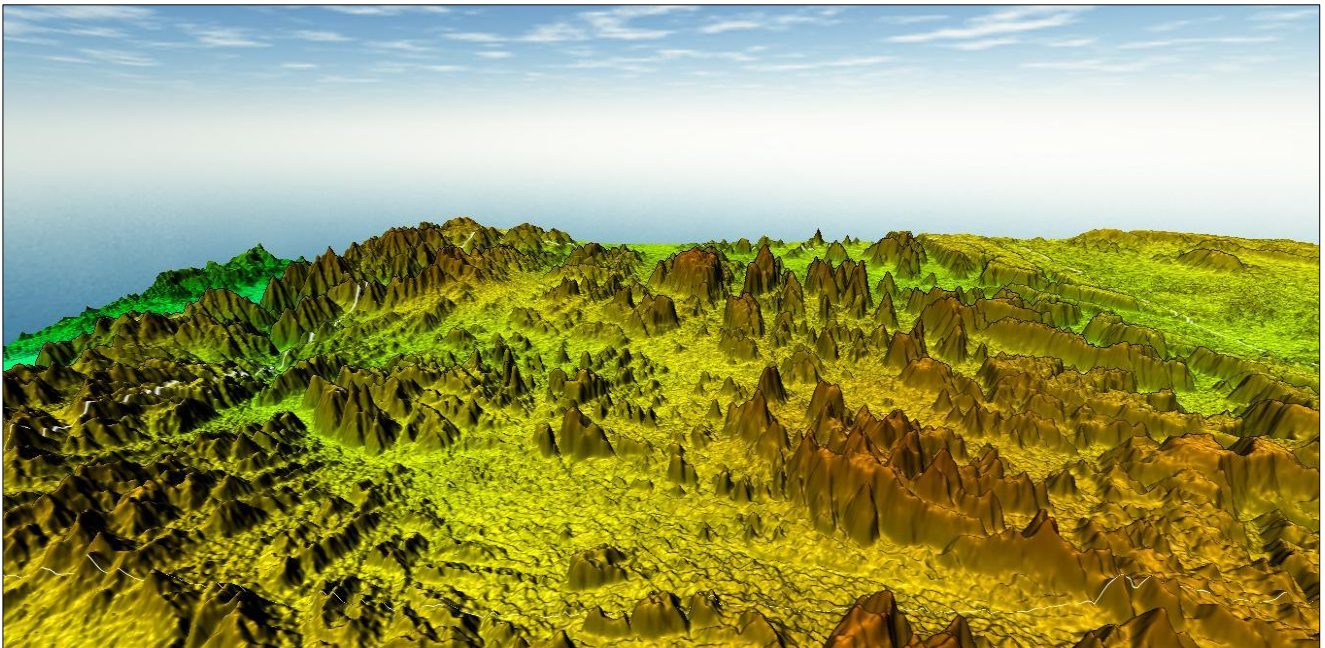


Figure 6. Digital Terrain Model (DTM) for Geomorphological Study of Wadi Rum
(Source: Author, prepared by the researchers using Global Mapper software)

Despite increasing research in this area, whether human behavior in Wadi Rum is influenced by natural landform features has received limited attention. The laws, decrees, and policies that govern land use in protected areas support the protected area's mandate to conserve and protect natural and historic resources for present and future generations. While management of a protected area is primarily about fostering biodiversity and ecological processes, historically, the management of those designated lands has increasingly been concerned with harmonizing the aims of biodiversity conservation with the interests of park visitors and tourism operators.

Wadi Rum is similar to many semi-arid rangeland systems in that the impacts of human activities are often complex, manifest in individual and joint actions, and difficult to separate from natural processes, particularly when they occur in accounting units as large as the Rum basin. It is widely recognized that the best integrative approach to management is to regard human society as part of an ecosystem and to actively engage in that ecosystem management. Ecosystem management is not management of the ecosystem per se, but rather management of how the people in that ecosystem interact and affect that ecosystem, now and in the future (Al Fahmawee & Jawabreh, 2022b).

Historical land use patterns in Wadi Rum Natural and Cultural Protected Area (WRHPA) can be divided into two groups: traditional and current/agricultural. The alteration between the two is the latest episode of increased agricultural production and development programs for the area. Traditional land use included agriculture in a subsistence mode of

production, extraction of stone for building, and herding (Jawarneh, 2021). Some 40 agricultural dams date back to the Nabatean and early Islamic periods in the wadis east of the mountain blocks of Wadi Rum, while more than 3,500 small domestic cisterns have been constructed in the mountains themselves. Little agriculture has been practiced in the wadis since the beginning of the last century, although clear historical marks of these activities, such as systems of stone slope terraces, remain (Groom et al., 2022; Bedair et al., 2021; Fattah et al., 2021; Jawabreh, 2020).

Changes in land use in Wadi Rum are a reflection of complex socio-economic dynamics, including economic opportunities and interventions related to international trends. Nationally, the effects of these structural changes are compounded by high birth rates, reduced services, and a public sector grappling with both underemployment and unemployment. While practices have changed significantly in terms of intensity, they have not necessarily changed in terms of geographical scope, and an understanding of historical land use trends is thus an essential contextual reference for present and future land use planning, and within this, for identifying opportunities and constraints for livelihood development and tourism potential (Noreldeen et al., 2023; Potjanajaruwit, 2023). Sustainable livelihood approaches in Wadi Rum, driven by cultural, historical, and ecological values, afford conservation and development objectives an opportunity to blend. Effective management of natural and cultural resources is essential for conservation purposes as well as to enable responsible resource use to support the local population.

2. Current challenges and pressures on landform characteristics

The Wadi Rum site faces many pressures and challenges, including human-induced and natural factors. A preliminary assessment of these pressures and their impacts on the landform characteristics is detailed in the summaries. These pressures vary from one type to another and range from global issues such as climate change and variability to regional ones, such as intensified agricultural activities, to national ones, such as touristic activities, in addition to urban development pressures, such as the urban development in Wadi Rum village and the Kings Highway area.

Given the importance of the landform characteristics, those pressures and their impacts were evaluated using available information, earth observations, historical data, and spatial analysis of anthropogenic activities (Lin et al., 2022; Sen et al., 2024; Seidualin et al., 2024; Sutiksno et al., 2024). The aforementioned pressures have visual and physical impacts on the landform characteristics. Present activities are affecting the geomorphological integrity and ecosystem health and may further increase the relative importance of the natural factors, given that it is beyond the range of change maintained by the geomorphological processes operating locally. Urgent interventions are necessary to minimize and arrest the decline of vital natural functioning and value. It is vital that policies and management practices provide an enabling environment for adaptation, protecting and maintaining the landform characteristics, and contribute to maintaining the resilience of the landscape components. Further understanding and assessment of the interplay and connectedness of the landform characteristics with other landscape components, people, and local economies that rely on them would help to identify gaps and provide solutions. A series of policy and managerial recommendations are detailed for maintaining and increasing the resilience of the landscapes, both internally and externally, as well as for the communities that live and work in them. Engaging relevant stakeholders in the assessment and decision-making processes and strengthening the role of communities and their institutions in the management of their landscapes is the optimal approach for reversing the deterioration of the landscape and ensuring some of its unique qualities. Local and global efforts should draw on local knowledge and practices in framing the desired future for the landscape.

3. Development recommendations based on geomorphological understanding

Based on the previous geomorphological overview and geodiversity synthesis, this section provides a number of recommendations for the development of the Wadi Rum Protected Area. These recommendations take into account any information from the previous sections, as well as the need for continuing systematic geomorphological mapping and research of Wadi Rum. The findings therefore also serve as a basis for future management strategies for the Wadi Rum Protected Area. Any kind of development in Wadi Rum should be based on the knowledge about its geomorphological structures and on the ecosystem as a whole. Uncontrolled and unsustainable development should be avoided if the area's landform characteristics are to be preserved for future generations. Initial studies on scientific geotrips for eco-tourists show that the majority would be interested in such trips if the knowledge was there to help content.

Other parts should be left for regulated ecotourism, especially guided by locals working together in cooperation and based mainly on the knowledge acquired through geomorphological mapping about the need for management. Furthermore, traditional, non-motorized tourism activities, like hiking, trekking, camel riding, and horse riding, should further be supported and developed. All development plans must be based firmly on principles and regulations regarding any construction projects and vehicles, and the planned expansion of any facilities in the area should be subject to an environmental impact assessment. Identifying large portions of complete ecological sites will also help in planning and emphasize connectivity – where species can pass through different areas to breed and feed. All those developments are mainly oriented and based on the geomorphological findings in Wadi Rum and created due to the mapping results (Delaunay et al., 2024; Sen et al., 2023; Sen et al., 2024; Georgiou et al., 2023; Jawabreh et al., 2021).

Sustainable Tourism Practices

Tourism can be an attractive reason to develop some underdeveloped areas and can be used for beneficial tourism purposes based on the characteristics of these areas. In some areas, educating tourists and raising awareness about the importance of these areas as natural heritage is very important (Kurar & Kavacik, 2023). Encouraging eco-friendly

forms of tourism in the area is also important since eco-tourism is often based on a limited area being preserved in a near-natural condition. For the Protected Area, we must provide all tourist facilities with minimal impact on the natural environment. In order to minimize the impact of tourism, tourists' movements must be restricted, especially the use of four-wheel drive vehicles. A suggestion should consider shifting tourists only onto roads instead of the open intermediate area of the desert, particularly where sand is present. This is feasible with a light vehicle atmosphere without any need for an ambulance, which can save a lot of petrol and, of course, has a lower risk of accidents because driving over sand is a more difficult and dangerous ride, especially without an experienced driver. (Dias et al., 2021; Voronkova et al., 2021; Ramadhani et al., 2021; Hutagalung et al., 2021; Le et al., 2024).

Many of the following measures and standards for the best available technical interventions in the area are specifically for the protection of landforms and the promotion of sustainable tourism. Particular attention has been given to the protection of landforms through the implementation of strategic techniques aimed at preventing landform erosion through artificial anthropic behavior influencing the ecological process. The involvement of citizens and the local community to participate mainly through participation in any conservation event, decision, activity, or managerial plan is a medium of effective public education. A joint project between the responsible manager and registered residents outside education programs through teaching within research programs can be beneficial. Towns, cities, and some larger villages surrounding the area can be particularly important for the provision of tools for collaborative stakeholder participation. The way of communication between conservationists and residents as stakeholders is important.

CONCLUSION

The geomorphological study has provided an extensive and clear understanding of the distinctive characteristics and features of various landforms in relation to their inherent structure and multifaceted development processes. This deep time regime, which encompasses a prolonged temporal scale, plays significant roles in not only the protection of the area but also informs its future strategic plans for sustainable development. It is valuable to interpret these features as a unique type of nature tourism, which could draw attention to the ecological and geological wonders of the landscape. The Harra sands, often referred to as one of the most sensitive and fragile elements of geodiversity in the protected area, serve as a vital reference point, as well as a crucial element for the safeguarding of national parks and reserves.

The subsequent dynamics that influence and anthropic stabilization of the shifted sands make the reclassification or deflation of the sand characteristics considerably easier to achieve. Meanwhile, the complete geodiversity of the sand material found within a nearby geological and climatic context, which spans from finely grained particles all the way to larger pebbles, requires further and more meticulous checks. Additionally, more comprehensive geodiversity studies would be necessary for such a natural site to effectively demonstrate the integral role of geomorphological diversity. This includes emphasizing landform structures within a desert system specifically with regard to geomorphological diversity, particularly if the influencing factors undergo changes over time.

It is crucial to continue the monitoring and study of landform characteristics in the Wadi Rum area due to the rapidity of the phenomena taking place and the effect of local elements. An interdisciplinary scientific effort and coherent multiple-scale studies are currently needed to address current and future challenges and strategies for managing and maintaining the environmental system. This integration of scientific knowledge and local knowledge, together with managerial capabilities, is necessary to manage all of these different systems in the protected area. In the Wadi Rum protected area, more studies should be carried out on the natural risks facing the site. It is important to look for the probability of increasing natural risks in the area due to global warming and future climate change. It is recommended to address many of these matters through future geological and geomorphological studies in Wadi Rum, along with the role and influence of ongoing climate change on the landform, for the sustainable development of the Wadi Rum area as a protected natural area. Considering the balance between the protection of ground integrity and the exploitation of the living requirements for inhabitants is a very crucial process. Such studies can be applied to other protected desert areas with similar official status, aimed at ecotourism. It is noted that the protection of special natural features within the fourth category of IUCN is carried out within limits that interfere with local traditions and customs.

For this reason, the democratic participation of people in the management of the areas must not be ignored. Communication between scientists, conservationists, and policy and decision-makers is crucial for discussing and fulfilling the needs of the present generation without undermining the role of the area in the future in this world of rapid transformations and abrupt environmental changes that reach many parts of the planet.

Applying sustainable development takes into account that harmonizing the requirements of people and nature in each place becomes, with the participation of local communities, a strategic objective that aims to preserve and develop land and territorial resources while preserving the biodiversity of natural systems with the need to respect and restructure.

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