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Identification of morphogenetic regions and the respective geomorphic processes: a GIS approach

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Abstract

A comprehensive investigation into the geographic or geomorphic phenomena of a region is crucial for various purposes such as managing resources effectively, and applying the acquired knowledge for regional development. The foundational step in such regional assessments lies in understanding the physical characteristics of the areas under consideration. In this context, the identification of morphogenetic region(s) is particularly significant for geoscientists, geotechnical experts, and planners. This study employed the Lewis Peltier models to analyze the Paveh Rood watershed basin, focusing on two key variables: average temperature and annual rainfall. To examine and categorize the weathering and geomorphological areas within the studied region, climatic data—specifically average annual rainfall and temperature—were obtained from five synoptic stations of the General Meteorological Department of Kermanshah. Subsequently, this data was input into GIS software for analysis. The Peltier models were applied to determine regimes for each station, including the assignment of weight values. The outcomes were then recorded in a database, and relevant maps were generated using ArcMap software. The findings revealed that, among the nine morphogenetic conditions outlined in the Peltier model, five are manifested in the climatic conditions of the region. In terms of weathering processes, it was observed that the oceanic, temperate, and Selva regions undergo significant chemical weathering, characterized by a robust washing environment. In contrast, the savannah and semi-arid regions, specifically the northwestern region and the center of the basin, experience moderate and weak weathering, respectively.

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Introduction

Weathering occurs when the Earth's surface rocks undergo physical, chemical, or biological processes, induced by factors such as wind, water, or climate (Rich, 1950). In regional studies, adopting a sympathetic perspective to visualize the distinct characteristics of morphogenetic regions is essential. This approach provides a framework for better interpretation, analysis, and comprehension of the physics unique to each region for planning and management. Such a regional study facilitates a comprehensive understanding of natural resource allocation. The Lewis Peltier models of climatic geomorphology stand out as the preferred tool for studying weathering processes, widely employed by geologists, geomorphologists, and related sciences for identifying and interpreting land surface shapes (Fowler and Petersen, 2003). Territorial climatic geomorphology, a scientific discipline describing the shape and distribution of landforms based on climate types, enhances our understanding further (Karam et al., 2013).

In each climatic zone, specific weathering processes result from the prevailing climatic conditions. Additionally, within each shaping zone, weathering processes align with the influencing factors and climate of the active area (Jafari Aghdam et al., 2012). The morphogenetic model (Peltier, 1950) is structured such that the wettest and warmest areas experience maximum chemical weathering, while the driest and coldest areas exhibit minimum chemical weathering. Frost activity (physical weathering) predominates in areas with very low temperatures, where mechanical weathering is favored over chemical weathering (Fowler and Petersen, 2004). Understanding the factors influencing shaping and weathering processes across different parts of a basin identifies potential geomorphic hazards and assesses the environmental potential of these areas. This knowledge plays a crucial role in civil engineering planning. Numerous studies globally, including Davis, Punk, Baudelaire, Troll, and Peltier, contribute to the understanding of weathering processes. This study addresses the gap in geomorphological research in Iran, particularly regarding weathering processes. Leveraging geographic information systems (GIS) and relevant variables, the research focuses on zoning different weathering areas in the study region. Notably, Doke et al. (2018), based on a GIS approach, identified five morphogenetic regions—Selva, Maritime, Moderate, Savanna, and Semi-Arid. This study contributes to the limited literature on geomorphological studies in Iran and enhances our understanding of weathering processes in the region.

Case study

Paveh Rood watershed basin with an area of 6976.6 hectares is located in Kermanshah Province at″58' 14° 46 46 to ″25' 24° 46 eastern longitudes and ″15 '00° 35 to ″25' 06° 35 northern latitudes. The highest altitude of the region is 3086 meters and the lowest altitude is 789.6 meters above mean sea level. The average annual rainfall of the basin is estimated at 479.76 mm, of which 76.46% falls in the first six months of the hydrological year. Of this amount, more than 336 mm evaporates and the rest with a volume of 40.58 million cubic meters flows as runoff in the basin (Figure 1).

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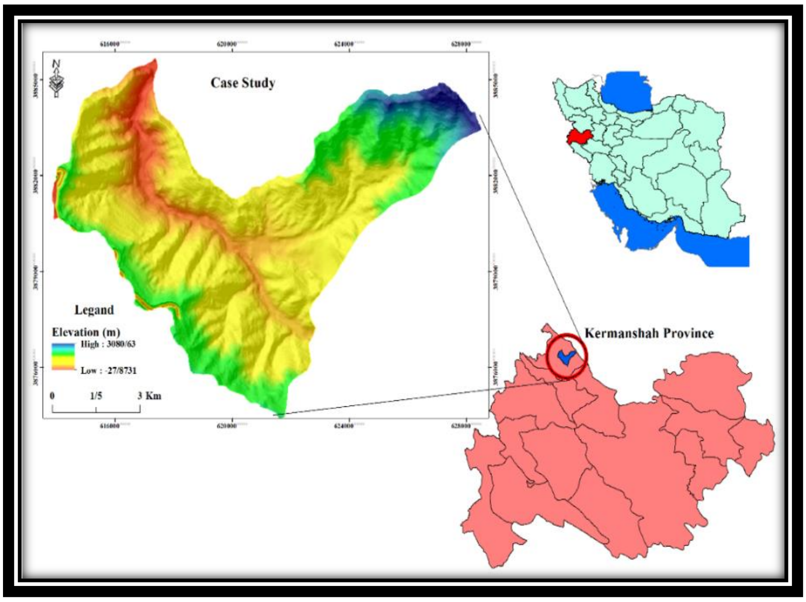

Figure 1. Location the study area in Iran

Materials and Methods

To map the morphogenetic regions of the Paveh Rood basin, this study assessed climatic data, specifically rainfall and temperature. Monthly and annual rainfall, as well as temperature data spanning the years 1998 to 2018, were sourced from the General Meteorological Department of Kermanshah province. Subsequently, the average annual rainfall and temperature data were computed to elucidate spatial variations in Paveh Rood's climatic conditions. The interpolation method, implemented in ArcGIS software version 10.3, was employed to generate rainfall and temperature maps.

Drawing on Peltier's (1950) criteria, which define the required rainfall and temperature for specific morphogenetic regions, the study classified spatial variations in rainfall and temperature into distinct morphogenetic regions and geomorphic process regions, as outlined in Table 1.

Table 1. Classification method to delineate morphogenetic regions (Modified after Peltier 1950).

Sr.no.	Morphogenetic	Estimated range of average annual rainfall (mm)	Estimated range of average annual temperature (°C)
1	Semi-arid	254–635	1.67–29.44
2	Savanna	635–1270	− 12.22–29.44
3	Moderate	889–1524	− 12.22–29.44
4	Selva	1897–5046	15.55–29.44
5	Maritime	1270–1905	1.66–21.11

After gaining an overview of temperature and precipitation trends, the morphogenetic characteristics of the area were investigated. Following the determination of each station's location in the Peltier model, a weight value, serving as a code, was assigned to each station and recorded in the database. To zone these characteristics using spatial interpolation and spatial analysis, the inverse distance weighting method was applied through GIS software. This model operates such that, at an intermediate level, the impact of a parameter on surrounding points varies, with closer points being more influenced and distant points having a lesser impact. Coefficients ranging from 1 to 4 were assigned for each condition, as detailed in Table (2), where the lowest coefficient corresponds to semi-arid regions and the highest to oceanic regions. Subsequently, a morphogenetic status map of the area was generated. In accordance with the criteria presented by Peltier (1950), the Query command in ArcGIS was employed to identify areas where rainfall and temperature parameters indicated different morphogenetic characteristics.

Table 2. Type of morphogenetic regions and their weight values.

Sr.no.	Morphogenetic	Weight values
1	Semi-arid	1
2	Savanna	2
3	Moderate	3
4	Selva	4
5	Maritime	5

If the estimation for a specific parameter within an individual morphogenetic region is available, but another parameter is not estimated, the value of the unestimated parameter is adjusted to the nearest values required by the morphogenetic region. For instance, if the rainfall meets the criteria for semi-arid conditions, but the temperature is close to the requirements without meeting them, the temperature values are adjusted to the required level for semi-arid conditions. It has been observed that the Peltier classification model assigns similar temperature and rainfall ranges to different morphogenetic regions. In such cases, a comprehensive field examination was necessary to precisely determine the morphogenetic region. The same methodology is applied to map different areas of geomorphic processes, including weathering, waterway erosion, and wind erosion based on Peltier models. Peltier graphs were generated for all these process areas, and the corresponding maps are embedded in the results section of this study. Rigorous fieldwork was conducted for validation, utilizing predominant unexpected geomorphic features to investigate existing morphogenetic regions.

The primary tools employed in this research were a 1:25,000 topographic map and a 1:50,000 geological map, both prepared by the Geological Organization of Iran and digitized using geographical information systems. Subsequently, a database was established within the GIS environment, and relevant data were incorporated into this environment. Digital elevation models (DEMs) and meteorological data from synoptic and rainfall stations were then utilized to identify weathering processes in the study area, culminating in the creation of relevant maps. Figure 2 depicts the elevation map of the study area, while Table 1 outlines the characteristics of the stations in the studied area.

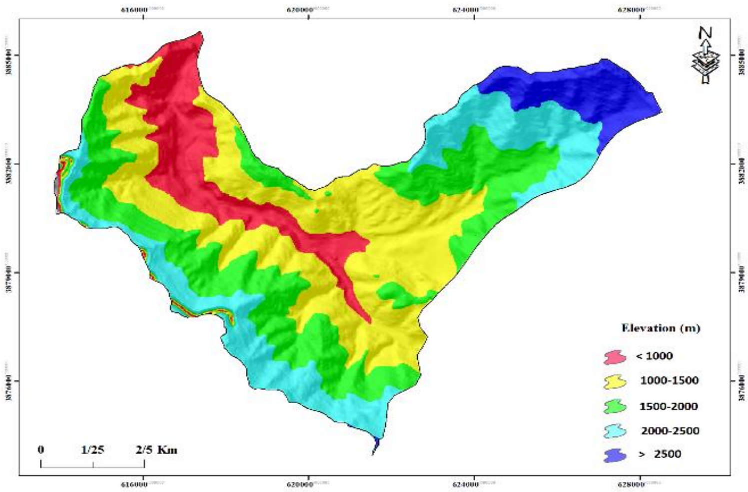

Figure 2. Elevation map of the study area.

Geology

The study basin is situated structurally at the termination of the middle segment of the high and folded structural zones of Zagros in Kermanshah province. The inherent characteristics of lithological units are generally a composite function of mineralogy and texture, which are pivotal factors influencing and determining the weathering potential and erodibility of the formations. The durability index stands out as a crucial engineering parameter for assessing the susceptibility of rocks to chemical and physical weathering factors, closely tied to the mineralogical and mechanical properties of rocks. To identify the weathering conditions in the Paveh Rood watershed, Peltier models were employed. Among the savanna Peltier models, two were selected that could effectively describe the weathering conditions and associated forms. The utilized models are outlined below:

Weathering regimes

Climate plays a pivotal role in determining the specific type of weathering, which, in turn, is influenced by the composition of the rocks present in a given area. The intensity and nature of weathering exhibit variations across different regions, attributed to geographical factors such as latitude, angle of radiation, altitude, proximity to the sea, and more. These variations generate distinct weathering conditions in accordance with the prevailing climate. The model employed here utilizes two variables, namely annual precipitation and temperature. It categorizes weathering into seven types, each indicative of specific weathering conditions. Table (3) provides details on the intensity and type of weathering based on the Peltier classification, accompanied by their morphological characteristics. Figure (6) visually represents the classification of weathering regimes in the Peltier graph. This model specifically incorporates average temperature and annual rainfall as its two variables, classifying weathering regimes into seven distinct classes. The design of the model ensures that areas characterized by warmer and wetter conditions exhibit maximum chemical weathering, while the driest and coldest areas experience the minimum chemical weathering. Notably, glacial activity, representing physical weathering, prevails in regions with extremely low temperatures, where mechanical weathering takes precedence over chemical weathering.

Table 3. The severity and type of weathering based on the division of the plotter along with their morphological characteristics.

Sr.no.	Intensity and type of weathering	Average annual temperature	Average annual rainfall
1	Very slight chemical weathering	-15 to +29	0-1015
2	Strong chemical weathering	13 to +29	>1525
3	Moderate chemical weathering	7.5 to +29	500-1525
4	slight Mechanical weathering	-18 to 7.5	0-880
5	Strong Mechanical weathering	-4 to -18	250-1300
	Moderate Mechanical weathering	-18 to -13, -18 to -1	500-1015, 100-1400

B) Morphogenetic regions

The model of morphogenetic regimes, aligning more closely with climatic and plant classifications than the weathering model, is illustrated in Figures 6. This particular model incorporates two variables—average temperature and annual rainfall—resulting in the classification of morphogenetic regions into nine distinct classes. Regions characterized by low temperatures predominantly fall under glacial areas, whereas those with high temperatures and low rainfall are identified as arid and semi-arid areas. Conversely, areas experiencing high rainfall and temperatures are classified as temperate and Selva regions. Table (4) provides a comprehensive overview of the morphogenetic regions based on the Peltier classification, along with their morphological characteristics.

Table 4. The morphogenetic regions based on the division of the Peltier with their morphological characteristics.

Sr.no.	Morphogenetic regions	Average annual temperature	Average annual rainfall	Morphogenetic characteristics
1	Glacial	-18 to -7	0 to 1400	Glacial erosion, Nivation
2	periglacial	-15 to -1	130 to 1400	wind performance, Strong mass movement, Slight running water activity
3	boreal	-9 to +3	250 to 1520	moderate action of glacial, Slight to moderate action of water and wind
4	Moderate	+2 to +21	1270 to 1900	Strong mass movement, moderate to Slight action of running water
5	Selva	+16 to +29	1400 to 2290	Strong mass movement, Sight Domain-leaching
6	Maritime	+3 to +29	890 to 1520	Strong action of running water, Slight action of glacial and wind
7	Savanna	-12 to +29	640 to 1270	Slight to Strong action of running water, moderate action of wind
8	Semi-arid	+2 to +29	250 to 640	Strong action of wind, moderate to Strong action of running water
9	Arid	+13 to +29	0 to 380	Strong action of wind, Slight mass movement, Slight action of running water

Results and discussion

To delineate the distinct morphogenetic regions of Paveh Rood using the classical Peltier model, this study evaluated the rainfall and daily temperature patterns (refer to Figure 3 & 4). The ensuing findings are organized into two sections representing various morphogenetic regions (see Figure 5), with additional details on different regions of geomorphic processes in Paveh Rood outlined in Figure 6.

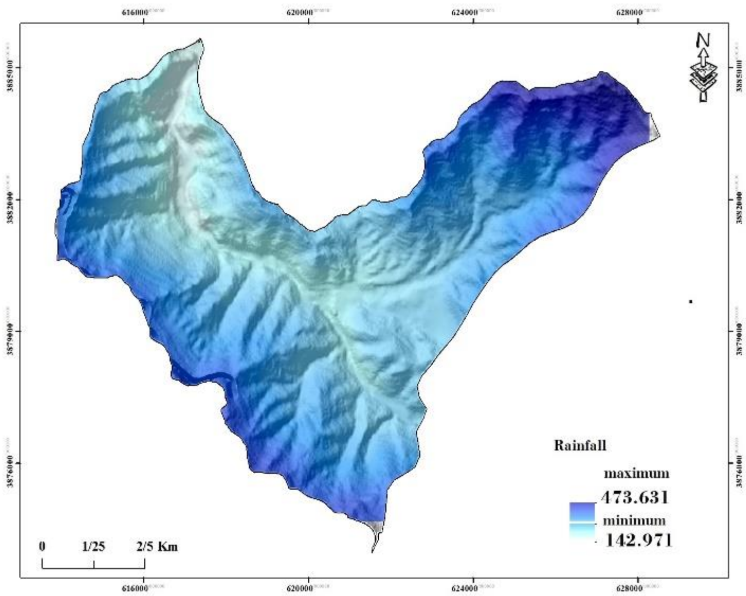

Figure 3. Rainfall distribution map of Paveh Rood.

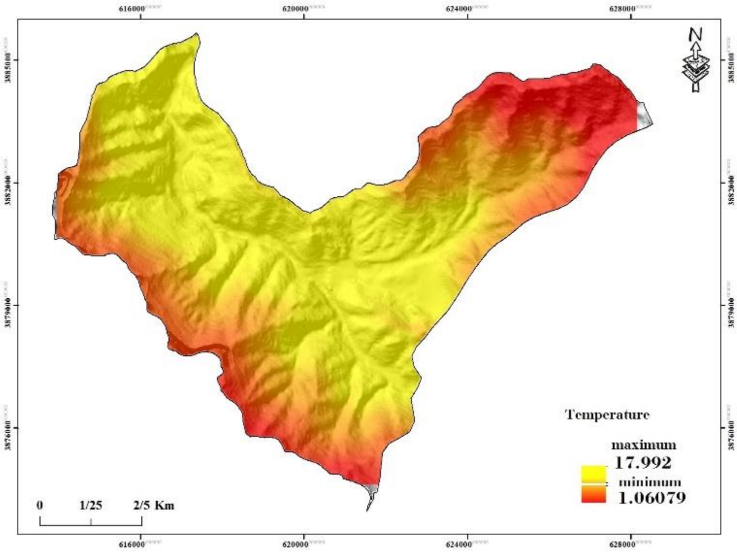

Figure 4. Temperature distribution map of Paveh Rood.

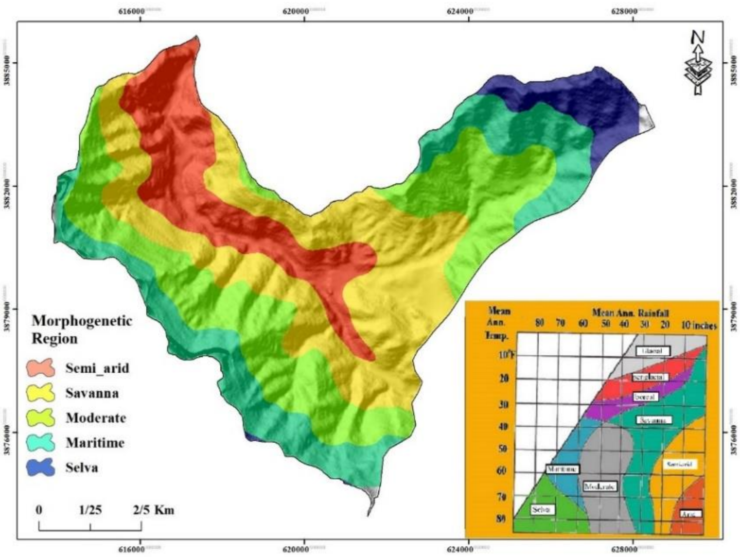

Figure 5. Morphogenetic regions of Paveh Rood based on Peltier's model. The inset graph was proposed by Peltier, and the regions are delineated according to the diagram.

Different morphogenetic regions

The results reveal that, among the nine morphogenetic conditions in the Peltier model, five are applicable to the climatic conditions of the region. Figure (3) illustrates the diversity in rainfall across the studied area, attributed to variations in topography. Rainfall systems move from west to east and southwest to northeast in the study area, bringing wet and rainy weather. Both systems, originating from the Mediterranean and the Red Sea (westerly winds), enter the region with a west-east and southwest-northeast direction. Upon colliding with the Zagros Mountains (west and southwest slopes), these systems induce rainfall in the region, with the increase in rainfall generally continuing up to an altitude of 2500 meters. The average annual rainfall in the Paveh Rood watershed is 652.7 mm, with approximately 70% occurring in autumn and winter. The region with the lowest annual rainfall, averaging less than 300 mm, is recorded in the northwest of the basin (Figure 3), with the minimum annual rainfall measured at 142 mm. The study area experiences an average annual temperature ranging from 7.27 to 23.6 °C. The estimated average annual temperature and potential evapotranspiration are 15.49 °C and 2265.64 mm, respectively. Figure 4 depicts the slope map of the studied area, with the majority of the Paveh Rood basin having a slope between 25 and 50 degrees. Five distinct morphogenetic regions are identified in the Paveh Rood basin: oceanic, Selva, temperate, savanna, and semi-arid, as shown in Figure 5. In many parts of the basin, where rainfall ranges between 450 and 650 mm, the savanna and semi-arid groups prevail. The semi-arid morphogenetic zone experiences negative water levels due to low average rainfall and high temperatures, resulting in water deficit, increased wind erosion, and reduced vegetation. Low humidity in the semi-arid region also contributes to decreased mass movement and chemical weathering. In the eastern part of the study area, where rainfall increases, the region falls under the temperate and Selva types of morphogenetic zones.

Different regions of the geomorphic process

The weathering process primarily involves the breakdown and alteration of materials under physico-chemical conditions in situ, without significant material movement. Weathering, therefore, exhibits a strong reliance on processes associated with the hydrosphere, atmosphere, and biosphere (Reiche 1950; Keller 1957; Ollier 1969; Selby 1993; White and Brantley 1995). Across the study area, rainfall distribution predominantly controls weathering activity, leading to the classification of weathering areas in the Paveh Rood basin into three categories: severe chemical weathering, moderate chemical weathering, and weak weathering (see Figure 6). The northeastern, western, and southwestern parts experience intense chemical weathering with profound chemical characteristics in the air. In the central basin, moderate chemical weathering is observed, while the northwestern and central regions show minimal chemical weathering processes. Alongside topographic considerations, geographical factors like altitude significantly impact degradation, weathering, erosion, and subsequent sediment production in the Paveh Rood watershed. Temperature variations induce cracks and fragmentation in rocks, particularly evident in the high altitudes of the watershed, resulting in loose soil due to physical rock destruction and the occurrence of Nivation. This loose soil is susceptible to transportation by rainfall, contributing to sedimentation. The phenomenon of scaly detachment or "onion skin" erosion, a consequence of desquamation, is another noticeable effect of pronounced temperature changes.

Furthermore, the geomorphological characteristics of the region play a crucial role and are among the influential factors in soil erosion within watersheds. Tectonic phenomena in the region's past and present influence characteristics such as hardness, grain sorting, ductility, and degree of cementation. Various parameters, including lithology, runoff, temperature, vegetation, and soil depression, collectively regulate the intensity of chemical weathering. Chemical weathering areas in the study zone are categorized into three groups: severe, moderate, and weak (refer to Figure 7). The western, northeastern, and southwestern regions of the Paveh Rood watershed exhibit significant chemical weathering attributed to heavy rainfall, while a smaller portion of the study area indicates low chemical weathering where rainfall is scarce (Figures 6 and 7).

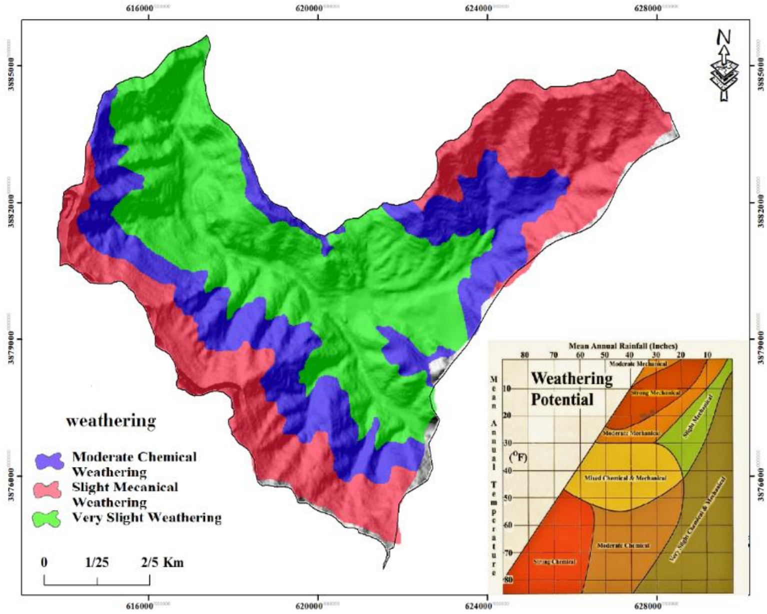

Figure 6. Weathering regions of Paveh Rood classified based on Peltier's model.

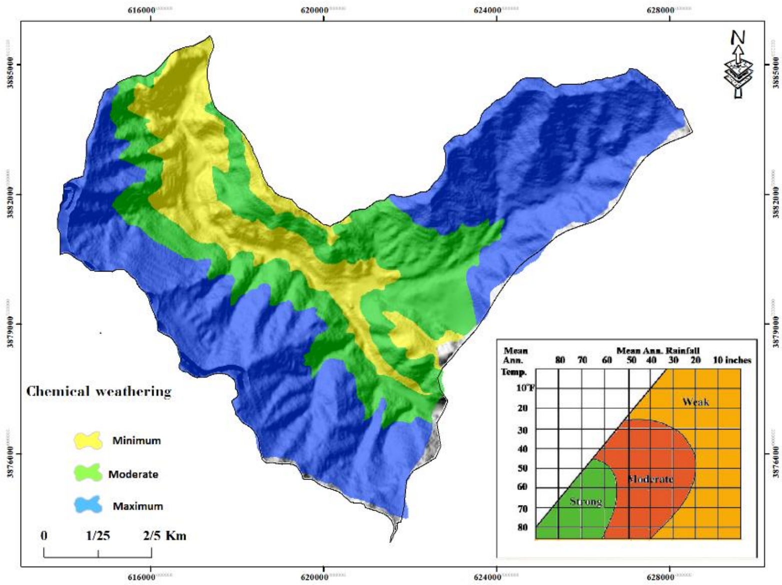

Figure 7. Chemical weathering zones based on the intensity.

Mass movement is also one of the most important geomorphic processes used by Peltier in his study. Landslides and sloping movements are often common in the Paveh Rood basin. The movement of the basin masses is expressed in three states: strong (maximum), medium and weak (minimum) (Figures 8, 9, 10 and 11).

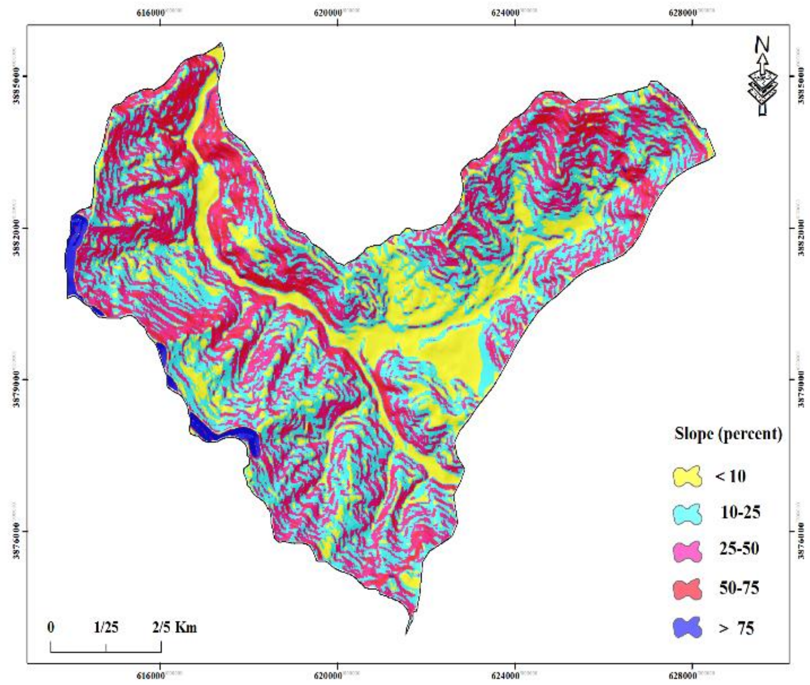

Figure 8. Slope map of the study area classified based on Young (1972).

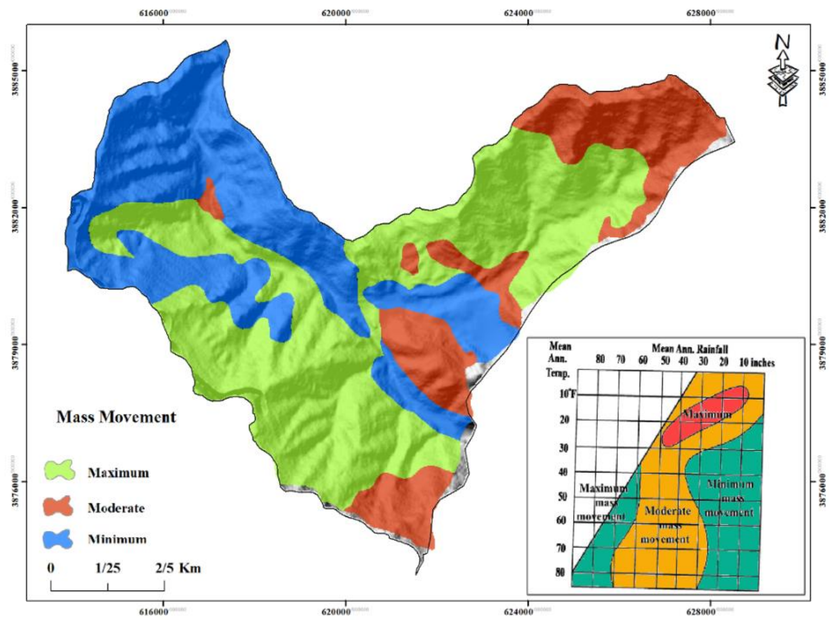

Figure 9. Mass movement regions of the study area.

Figure 10. An example of roadside landslides on Jkr rock facies due to road excavation. The fragmented structure of the area shows a high potential for landslides. Photo from Foriab Road to the northwest.

Figure 11. An example of marginal falls located on the sedimentary facies of Garo Formation. Photo of the main road of the basin before Dasheh village - Dideh to the west.

Areas with precipitation ranging from 650 to 75 mm exhibit the highest susceptibility to mass movement. In Figure 7, regions with low rainfall (semi-arid) are depicted as having the lowest mass movement, with a limited area in the study zone influenced by medium mass movement. Examples of landslides and falling movements in the area are illustrated in Figures 10 and 11. Given the structural characteristics and slope of the region, the occurrence of mass movements, particularly in the southern and western parts of the basin and on "kg" and "JKr" outcrops, can be anticipated in the event of an earthquake. The study area was also assessed in terms of strength, with the predominant formation covering the area comprising resistant facies and calcareous limestone of the Garou geological Formation, along with radiolarity and JKr silica limestone scattered across an area of 6289.47 hectares (93% of the basin area) as illustrated in Figure 12.

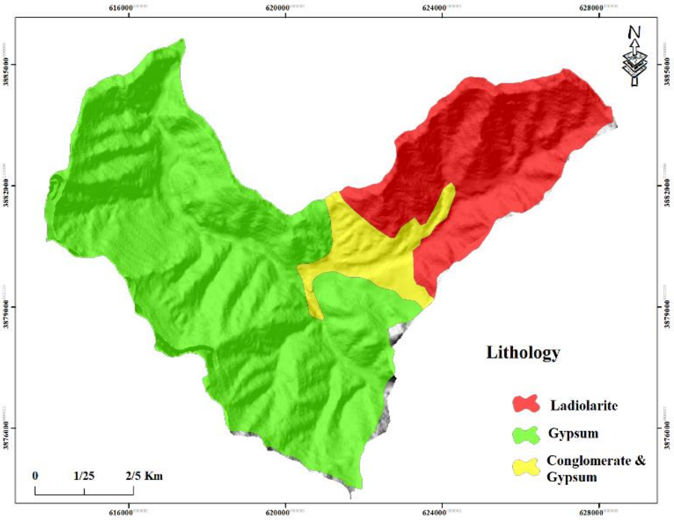

Figure 12. Lithology zones in Paveh Rood

Due to the fragmentation and extensive development of fracture and seam systems, coupled with their high permeability, these areas generally exhibit a low water waste coefficient. With the exception of heavy rainfall conditions, they do not facilitate water flow, resulting in a low flow rate and minimal susceptibility to flooding and sedimentation. These facies are distributed across most areas of the basin. River erosion primarily stems from the degradation and dissolution of waterway walls, with a higher likelihood during floods and wet seasons. As the river's water volume increases, so does its sediment carrying capacity. This heightened flow carries a significant amount of suspended sediment, intensifying erosion along the riverbanks. The erosive potential of water with a high concentration of suspended solids surpasses that of pure water. Key factors influencing river erosion and sediment transport include the river's slope, the potential for flood flow, the type of rocks along the riverbed, and, most importantly, the nature or sensitivity of the formations. A study involving a tracer experiment was conducted to observe precipitation erosion mechanisms. Ploey (1972) conducted a quantitative comparison of rainfall erosion capacity between a tropical region and a mid-latitude region. Morin and Van Winkel (1996) investigated the impact of rainfall on erosion processes. River erosion is categorized into three sections: strong, medium, and weak (refer to Figure 13).

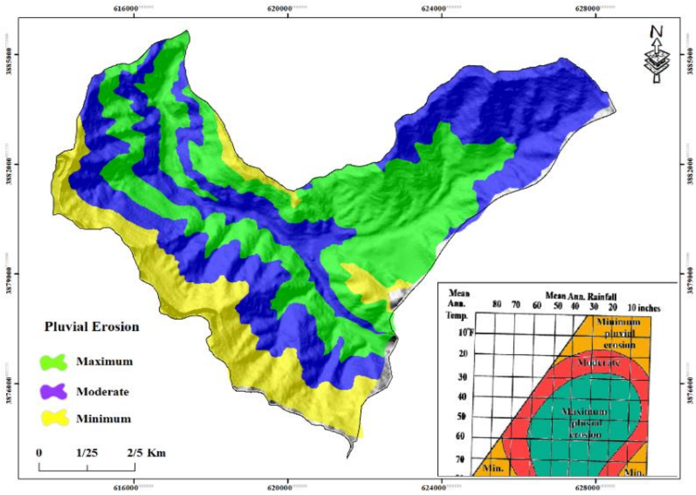

Figure 13. Pluvial erosion zones in Paveh Rood.

In regions with low rainfall, particularly in semi-arid areas, the primary cause of elevated erosion from rainfall is the absence of vegetation. Wind erosion involves the separation, transport, and deposition of soil particles driven by wind action. Within the Paveh Rood basin, areas affected by wind can be categorized into three main groups based on wind strength: strong, medium, and weak (see Figure 12). The northwestern region exhibits moderate wind activity, while the western, northwestern, southwestern, and southern regions experience the maximum wind activity. The remaining portion of the basin demonstrates weak wind performance (refer to Figure 14).

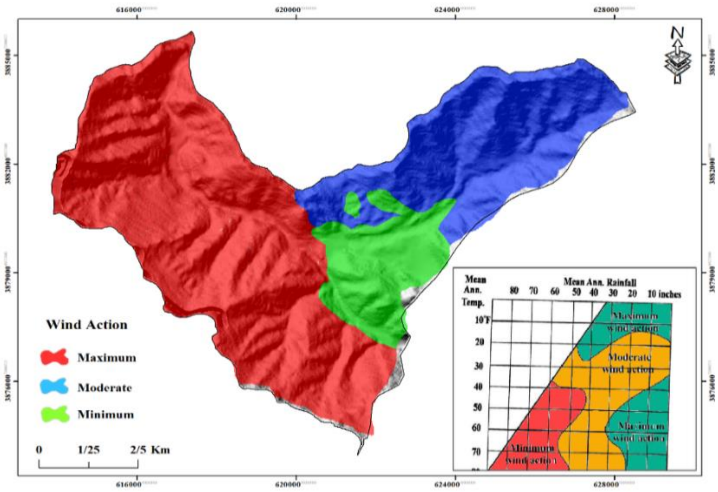

Figure 14. Wind action map of Paveh Rood based on Peltier's model

Conclusion

The mapping of morphogenetic regions utilizing the classical Peltier model offers a precise depiction of geomorphic processes influenced by the climate in the Paveh Rood watershed, Kermanshah province, Iran. The findings reveal that the temperature and precipitation patterns in the region are significantly influenced by latitude, the orientation, and elongation of elevations, leading to diverse conditions across various parts of the region, particularly in the context of elevations and their orientations. These factors play a pivotal role in shaping weathering regimes and associated landforms. Among the nine morphogenetic conditions identified in the Peltier model, five conditions align with the climatic conditions prevalent in the region. The analysis of rainfall and temperature distribution across the entire study area delineates five distinct morphogenetic regions: 1) Semi-arid (11.88 km²), 2) Savannah (21.44 km²), 3) Moderate (19.95 km²), 4) Selva (4.08 km²), and 5) Oceanic (13.52 km²). Each of these morphogenetic regions is characterized by a spectrum of dominant processes. Due to varied topography, the studied area exhibits diversity in rainfall distribution, with mountainous regions predominantly classified as part of the Selva and temperate areas.

The Selva and temperate regions exhibit the predominant activity of flowing waters, ranging from intense to weak, along with a substantial impact of prevailing winds. Conversely, the northwestern parts and the center of the study area are categorized as semi-arid and savannah regions due to their moderate rainfall and temperatures, occupying a significant portion of the northern basin. In terms of weathering processes, the oceanic, temperate, and Selva regions experience robust chemical weathering, characterized by a vigorous washing environment. In contrast, the savannah and semi-arid regions, encompassing the northwestern and central basin, undergo moderate and weak weathering, respectively. The output map of the weathering model indicates that weathering conditions are influenced by the topographic and climatic factors of the region. Furthermore, the study highlights that mass movement is most pronounced in temperate and savannah regions, least in semi-arid regions, and moderate in Selva regions and parts of temperate regions in the south of the basin. River erosion is most prevalent in the Savannah region, moderate in the Selva, semi-arid, and temperate regions, and weak in the oceanic region. Wind activity varies, with weakness observed in the east and center of the basin (part of the semi-arid and savannah region), moderate in the Selva and temperate regions, and the northeastern part of the oceanic region. Maximum wind activity is concentrated in other oceanic, semi-arid, and savannah regions, particularly in the center, northwest, southwest, and west of the basin. Beyond the immediate findings, this study holds significance for future climatic, geomorphic, and geological investigations in the studied area.

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