

Decoding Landscape Evolution: A Geomorphometric Approach to the Lebanese Terrain

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ABSTRACT

Theories of landscape evolution by Davis, Penck, and King describe the development of terrain through successive stages, but the choice of the most suitable model for a particular region needs to be supported by quantitative geomorphometric evidence. This study addresses two questions: which descriptive model best explains the topographic evolution of Lebanon, and at what stage of its development the present terrain is. Strahler stream orders 3 to 11 were used to construct nine isobase surfaces using GIS-based hydrological analysis with ALOS digital elevation models at 12.5 m resolution. The hypsometric integral, hypsometric curves, fractal dimensions, profile curvature, relative relief, and a modified surface index were used to characterize each surface. Results show a proportional decrease in slope and elevation with increasing number of isobases. Isobases 5-7 are indicative of equilibrium landscape development, while isobases 8-9 represent an older, disequilibrium stage. Of the three competing theories, Penck's model of simultaneous uplift and erosion best explains Lebanon's terrain, given its tectonic history along the Dead Sea Transform Fault System. The results are used to create a predictive landscape evolution map of Lebanon, defining five spatial zones of progressive terrain dissection. Besides the Lebanese context, the proposed isobase-based geomorphometric framework provides a reproducible methodology for other tectonically active regions and a physiographic baseline for future geological mapping, tectonic analysis, and natural hazard assessment.

Keywords: Geomorphometry; DEM; Isobase; terrain evolution; Davis; Penck

Introduction

Geomorphologists have reconstructed landscape history using methods that map sedimentary features, terrain configurations, and geological structures. Their approach depends on identifying present-day manifestations of geomorphological processes to understand landscape evolution.

Geomorphology is the study of the origin and evolution of landforms and landscapes shaped by the ongoing interaction of internal forces within the Earth and surface processes. Landscape development begins with

endogenous processes such as tectonic uplift, faulting, and crustal deformation. These processes create topographic relief and provide a framework for the Earth's surface. When rocks are exposed, they are weathered into loose material ready for transport. Gravity-driven slope processes such as landslides, rockfalls, and soil creep then move this material downslope. Erosional agents such as rivers, glaciers, wind, and waves continue to erode, transport, and redistribute sediment across the landscape. Finally, as the energy of the transport

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agents diminishes, sediment accumulates, contributing to the formation of new landforms. All these processes are interconnected and together constitute a dynamic system. Tectonic forces produce topography; weathering and slope processes supply and transport sediment; and erosion, transport, and deposition modify Earth's surface over time. These processes result in changes to drainage patterns, slope configurations, and overall landscape transformation (Burt et al., 2008).

Throughout history, scientists have used various terms to describe landscape evolution, including erosion cycles, slope evolution, and geographic cycles, as articulated by early scholars such as Davis (1899), Penck (1953), King (1953), Hack (1960), and Crickmay (1974).

William Morris Davis, an influential figure in the field, introduced a seminal model for the sequence of landscape evolution. According to his framework, the process begins with rapid uplift, which provides the fluvial system with the potential energy needed to erode the landscape. This erosion progresses through juvenile, mature, and old-age stages, typically characterized by tectonic stability (Davis, 1889, 1899, 1909). The terrain's slope gradually decreases, forming a low-relief plain near the riverbed (Figure 1).

In continental Europe, Davis's theory found less resonance, as geomorphologists adopted the modifications to landscape evolution theory by Walther Penck and Lester C. King, leading to divergent approaches across regions.

In his theory, Davis classified landscape development into youth, maturity, and old age (see Figure 1a).

Penck introduced a different terminology for his model, using the phrases “increasing or accelerating rate of development,” “uniform rate of development,” and “decreasing or decelerating rate of development” instead of the three traditional stages (see Figure 1b) (Von Engel, 1960).

Alongside Davis's consideration of uplift and crustal stability in his erosion cycle, King's framework divided the stages of land development into young, mature, and old phases (see Figure 1c).

King's geomorphic systems, including landscape, pediplanation, and hillslope models, were primarily shaped by South Africa's characteristics, particularly its arid and savanna regions. King argued that Davis's dry-erosion cycle was relevant to the South African landscape (King, 1953).

According to Davis, the erosion cycle in wet temperate countries primarily manifests in fluvial landscapes, featuring an increase during the juvenile phase followed by a decrease with age (Davis, 1905).

King (1953) describes pediplanation as a process of relief reduction by the parallel retreat of slopes, leading to the formation of extensive pediplains. He claimed that landform evolution is a phased process rather than staged as proposed by Davis and that climate is an important factor in controlling the geomorphic cycle (King, 1953; Summerfield, 1991).

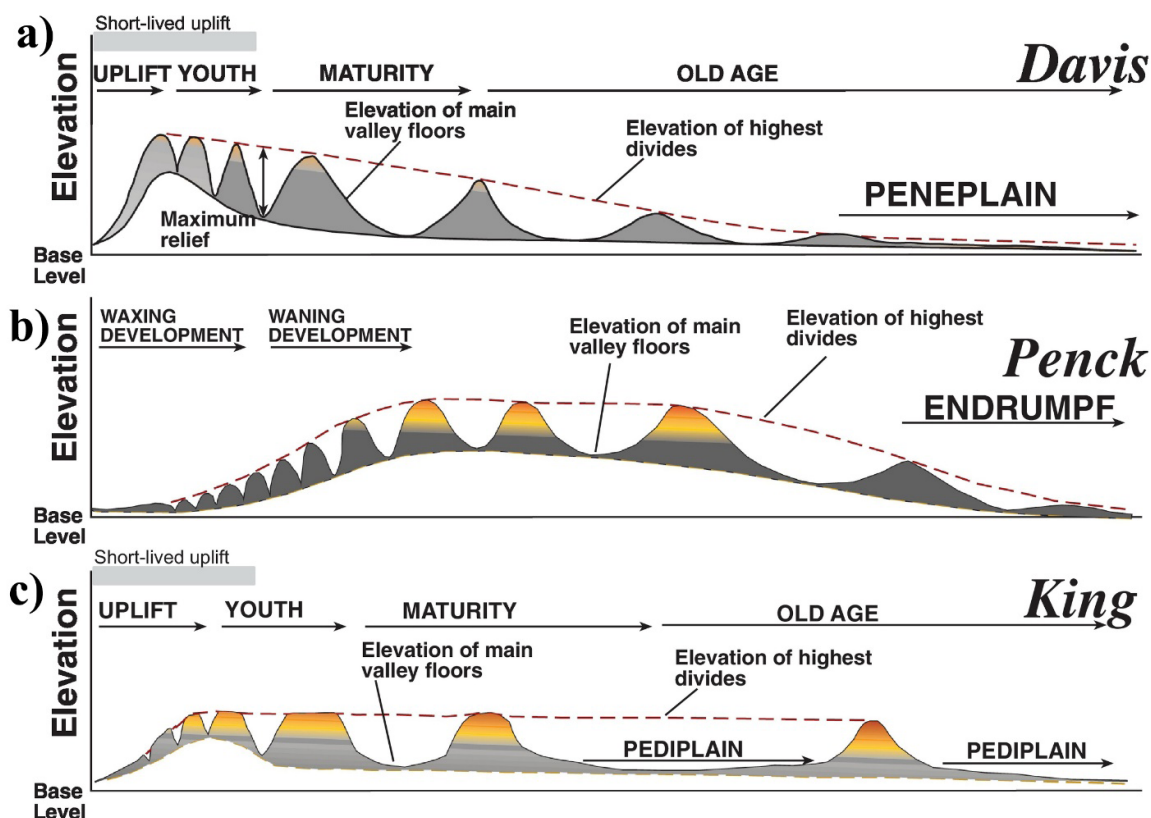


Figure 1. Landscape Evolution Profiles: (a) Davis' Landscape Evolution Theory, (b) Penck's Theory, (c) King's Theory (Adapted from Vasconcelos & Carmo, 2018).

Table 1. A summary of Davis, Penck, and King's theories.

Davis' theory (Davis, 1899)	Penck's theory (Penck, 1953)	King's theory (King, 1953)
Sudden Upliftment.	The long process of Upliftment.	Sudden process of mountain Upliftment.
Erosion starts after the uplift stops.	Upliftment and erosion are simultaneous.	The erosion process begins after uplift ceases.
Landform refers to the process of weathering, which is carried out by agents such as wind, air, groundwater, and sea waves. Landforms are classified into three stages: youth, maturity, and old age.	Landforms reflect the combined effects of endogenic and exogenic forces. Landform development is classified in phases rather than stages.	Landforms are in equilibrium with the climate and do not affect their development cycle. Landscape development is a cyclical process and is classified into three stages: youth, maturity, and old age.

Table 1 compares the theories proposed by Davis, Penck, and King. It also presents hypotheses about which theory may apply to the landscape evolution of Lebanon, leading us to pose the following questions:

As Philip G. Worcester postulated, the landscape evolution (or erosion) cycle is the time it takes for rivers to reduce newly formed landmasses to their original levels (Worcester, 1958).

Water and rivers are the primary agents of erosion, while water-related processes significantly shape much of Earth's surface (Hamood, 2009).

The drainage network and its sensitivity to factors such as lithology and climate act as reliable indicators of tectonic activity. Flows of similar orders are frequently associated with comparable geologic events and ages (Horton, 1945; Golts & Rosenthal, 1993; Strahler, 1952).

Numerous scientists, including Gravelius (1914), Horton (1945), Dury (1952), Strahler (1957), Filosofov (1960), Pannekoek (1967), Golts and Rosenthal (1993), and Florinsky (2012), have studied landscape evolution based on stream networks, where erosion networks assign relative geologic ages to various stream orders.

Isobase plains represent hypothetical plains formed by connecting stream profiles of similar stream orders. They serve as indicators of basalt plain erosion, are associated with comparable erosional phases, and potentially represent erosion-tectonic events (Filosofov, 1960).

The analysis of isobase areas can yield valuable insights, including 1) the identification of young tectonic processes; 2) the creation of morphotectonic maps; and 3) the delineation of tectonic areas and their movement directions (Gary et al., 1973).

This paper reports the construction of isobase maps of Lebanon based on stream-order hierarchies to evaluate landscape evolution patterns and assess the applicability of established geomorphological models. The isobases concept used in this research is based on the methodological approach of Filosofov (1975) and Golts and Rosenthal (1993) and is conceptually associated with the sub-envelope surface approaches developed

by Hack (1960) and subsequently extended in geomorphometric studies such as Gomez et al. (2006). These methods are often used to define geomorphic surfaces at the regional scale and to identify possible tectonic influences on landscape development.

Recent advances in Geographic Information Systems (GIS) and high-resolution Digital Elevation Models (DEMs) have considerably improved the capacity to quantitatively analyze topography and landscape evolution. These technologies are now widely used in tectonically active areas, such as mountain belts in the Himalayas, the Andes, and the Mediterranean, to determine morphometric indices, quantify uplift and erosion patterns, and characterize the organization of the drainage network. In particular, the application of isobase mapping, hypsometric analysis, and other related geomorphic metrics has been successfully used to differentiate spatial variations in geomorphic maturity and to identify areas affected by neotectonics activity, even in the presence of complex lithological variations.

However, integrated regional-scale studies that apply isobase-based geomorphometric analysis, combined with multiple morphometric indices, to reconstruct landscape evolution are still lacking in Lebanon. Previous studies in the region have largely been limited to localized basin-scale studies or structural geological interpretations, with few applications of comprehensive DEM-derived quantitative frameworks at the national scale.

This study is intended to fill this gap by integrating isobase mapping with a variety of morphometric techniques, including stream-order statistics, bifurcation ratio, hypsometric curves, hypsometric integrals, relative and anomalous relief, fractal dimension analysis, profile curvature, and surface roughness indices. These parameters are determined using GIS- and DEM-based algorithms to assess spatial variations in landscape form and evolutionary stage across Lebanon.

The scientific contribution of this research is the first systematic, region-wide application of isobase surface analysis, integrated with multi-parameter morphometric evaluation, in Lebanon. Results are ex-

pected to provide a quantitative framework for interpreting landscape evolution, identify spatial patterns of uplift and erosion, and evaluate potential tectonic controls on drainage development. In addition to the geomorphological implications, the study has practical implications for tectonic geomorphology, watershed management, environmental planning, and studies of landform evolution in structurally complex mountainous regions.

In this experimental study, we will use morphometric indices of isobase surfaces, such as the hypsometric curve, relative and anomalous relief, fractal dimensions, profile curvature, hypsometric integral, surface roughness, and surface index, to address these questions:

1. Which of the proposed theories is best suited to explain the landscape evolution of the Lebanese terrain?
2. What is the latest evolutionary stage, as shown in Figure 1?

Material and Methods

a) Study area and datasets

The Lebanese landscape comprises three primary geomorphological structures: the Western Lebanon Mountains, culminating at Cornet Es Sawda at 3083 meters above sea level; the Bekaa Valley; and the Eastern Anti-Lebanon Mountains, dominated by Mount Hermon, which rises to 2814 meters above sea level.

Lebanon's river network can be categorized into two groups. The first group comprises 12 major rivers that drain the Lebanese mountain range and flow through steep gorges. The second group includes the two major rivers, Litani and Al Assi (Orontes).

The geological evolution of Lebanon unfolds in five distinct episodes:

- 1) Late Permian to Late Triassic, marked by initial rifting.
- 2) The Early to Late Jurassic was marked by stability and warm, clear seas, with the oldest rocks in Lebanon dating back to the Lower Jurassic.
- 3) The period from the Late Jurassic to the Middle Cretaceous is marked by uplift, volcanic activity, and the development of deltas linked to the pre-Chouf sandstone uplift.
- 4) From the Late Cretaceous to the early Eocene, characterized by high seas and gentle folding.
- 5) From the Middle Eocene to present times, tectonic uplift and climatic cooling have taken place, particularly emphasized by significant uplift during the late Eocene and Oligocene (Walley, 1998).

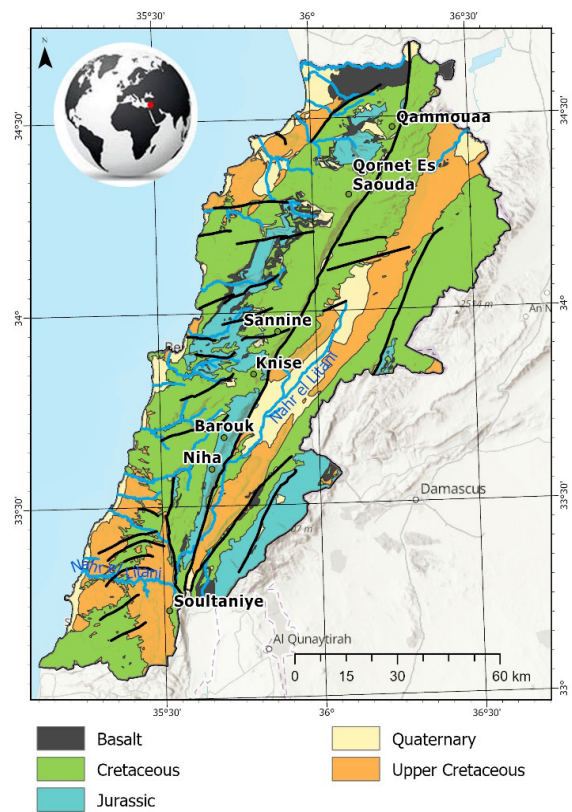


Figure 2. Lithology map of the study area highlighting landscape structures.

The study area was significantly influenced by the initial movements of the Dead Sea Transform Fault System, resulting in tilting, uplifting, and disruption of drainage patterns.

Throughout various geological episodes, persistent uplifts and significant disruptions in water flow occurred as different blocks slid past one another along strike-slip faults. A noteworthy example of this phenomenon is the Litani River, which likely once flowed southward into the Jordan Valley but was redirected eastward toward the Mediterranean by uplift (Dubertret, 1934, 1947; Walley, 1998).

Leveraging Penck's theory, which accounts for the geological episodes in Lebanese geology, we can construct isobase surfaces and compare their geomorphic indices to understand the landscape's evolutionary processes.

The accuracy of surface modeling and morphometric analysis hinges on the quality of digital elevation models (DEMs) and sample size. The Advanced Land Observing Satellite (ALOS) DEM, available on the Alaska Satellite Facility website, provides elevation data with a spatial resolution of 12.5 meters (Logan et al., 2014).

b) Drainage System Extraction

Before generating stream networks from the DEM, it is essential to fill the model's nested wells to ensure proper flow direction and to prevent artifacts that could

obstruct the flow path. Using ArcGIS Pro's hydrologic analysis tools, we generated and classified streams by Strahler order.

The drainage system was extracted using GIS hydrologic methods, including drainage direction, flow accumulation, and stream order calculations for each pixel. Then, the extracted flows were ordered according to Strahler's (1957) hierarchy (Doumit, 2017).

c) Isobase Surface Construction

The spatial translation of stream elevations into isobase surfaces provides significant value for structural, geological, and tectonic studies (Dury, 1952; Filosofov, 1960; Golts & Rosenthal, 1993; Grohmann et al., 2007, 2011).

According to Golts and Rosenthal (1993), streams of similar order indicate similar geologic events and belong to comparable geologic ages. Interpolating elevations of these streams generates isobasic surfaces that represent the same erosional events. Variations in topography within an isobasic surface can help identify potential structures or elevated blocks associated with structural landscape evolution (Golts & Rosenthal, 1993; Grohmann et al., 2007; Domínguez-González et al., 2015).

Preparing isobasic maps begins with an initial sketch of valley orders, excluding all valleys except those of the last order from the second-order base contour. The third-order base outline includes all valleys except those of the first and second orders, and so on (Dury, 1952; Filosofov, 1960; 1970; Pannekoek, 1967).

Isobase areas for orders 1 and 2 were excluded, while higher-order terms were applied to alluvial modeling. Subtracting the older order (n) base area from the younger ($n-1$) results in a residual map of order $n-1$. This map illustrates the extent of erosional dissection in the area over the time elapsed between the formation of these two basal surfaces.

The recent hilltops in Lebanon exhibit Pliocene-Quaternary uplift. An envelope surface tangential to the interfluvies was determined by interpolating ridge-network elevations derived from the DEM. The last isobase surface of order nine serves as an under-envelope. Surface (end hull or peneplain).

Geomorphometry involves the quantitative measurement of landscapes, facilitating the characterization of landforms by their geometric shape and size. These measurements enable geomorphologists to objectively compare landforms and calculate parameters essential for identifying specific regional features, such as the degree of tectonic activity (Keller & Pinter, 1996).

To quantitatively analyze the landscape represented by the generated isobase surfaces, we calculated geomorphometric indices such as:

1. Hypsometric curve (H_c)

The hypsometric curve represents the distribution of elevations over a land area (Strahler, 1952). It provides

insights into elevation variation across the landscape. Hypsometric curves have helped decipher the evolution of drainage networks and can serve as valuable tools in distinguishing between active and inactive tectonic areas (Keller & Pinter, 1996). The curve is constructed by plotting cumulative elevation against total area (see Figure 8). Convex hypsometric curves typically characterize youthful, recently eroded areas, while S-shaped curves indicate regions with moderate erosion. Concave curve shapes are associated with eroded, older areas (Strahler, 1957).

2. Relative relief (R_r)

Relative relief (R_r) is the difference between the highest and lowest elevations in an area. R_r emphasizes the complexity and patterns of elevation variation (Doumit & Kiselev, 2019).

$$R_r = Z_{max} - Z_{min} \quad (1)$$

Relative relief in a relative velocity index of landscape evolution and vertical tectonic movements (Florinsky, 2012); high R_r values indicate elevated surfaces (Scotti et al., 2014).

3. Fractal dimensions (FD)

Mandelbrot (1982) introduced the fractal dimension to measure texture and evaluate complex forms. The experiment investigated the fractal dimensions of isobase surfaces to understand how they evolve with changes in the landscape. The formula for fractal dimensions is based on calculated slopes and seeks a linear relationship between precision and length in a log/log plot:

$$FD = \frac{\log(2)}{\log(2) + \log(\sin(\frac{180 - \text{slope}}{2}))} \quad (2)$$

Fractal dimension values of a surface range from 2 to 3, indicating surface heterogeneity; low values correspond to flat, smooth areas, while high values correspond to complex areas (Doumit, 2017).

4. Profile curvature (P_c)

Generally, curvature is calculated from a surface representation using a partial quadratic equation (Zevenbergen & Thorne, 1987).

Profile curvature or vertical plane curvature, P_c , is parallel to the slope direction and defined as

$$P_c = \frac{-2(DH^2 + EG^2 - FGH)}{(G^2 + H^2)} \quad (3)$$

Where:

$$D = \frac{z_4 + z_6 - z_5}{d^2};$$

$$E = \frac{\frac{z_2+z_8}{2}-z_5}{d^2};$$

$$F = \frac{-z_1+z_3+z_7-z_9}{4d^2};$$

$$G = \frac{-z_4+z_6}{2d};$$

$$H = \frac{z_2+z_8}{2d}$$

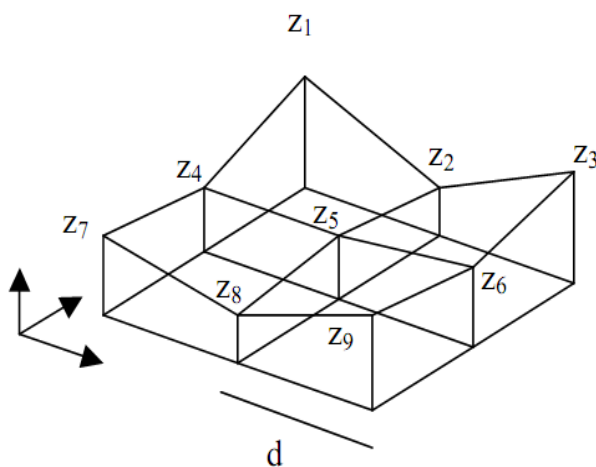


Figure 3. DEM 3×3 Matrix of profile curvature calculation (Doumit, 2017).

Profile curvature is a measure of the rate at which water drains across the surface, influenced by changes in slope. It plays a pivotal role in erosion and deposition processes. It is typically positive in convex areas, indicating a tendency toward erosion, and negative in concave areas, indicating a propensity for deposition. These characteristics describe the second accumulation mechanism (Zevenbergen & Thorne, 1987).

In areas with convex curvature, erosion predominates, whereas areas with concave curvature are more prone to deposition (Evans, 1980; Doumit, 2017).

5. Hypsometric integral (HI)

The hypsometric integral is the distribution of surface area with respect to elevation, evaluating the landscape response to active tectonics (Strahler, 1952; Mahmood & Gloaguen, 2012; Domínguez-González et al., 2015).

Pike and Wilson (1971) calculated the Hypsometric Integral with this equation:

$$HI = \frac{z_{mean}-z_{min}}{z_{max}-z_{mean}} \quad (4)$$

Where Z_{mean} , Z_{min} , and Z_{max} are the mean, minimum, and maximum elevations of the study area.

6. Surface index (SI)

The surface index, like the hypsometric integral, measures erosion and determines a landscape's maturity. In line with research by Andreani et al. (2014) and Domínguez-González et al. (2015), combining DEM elevations with the hypsometric integral and surface roughness enables classification of landscapes based on their state of dynamic equilibrium. This approach allows discrimination between areas with low local relief and those with rugged terrain (Andreani et al., 2014).

To calculate the surface index (SI), it is essential to normalize the DEM, hypsometric integral, and surface roughness values so that pixel values range from 0 to 1.

$$SI = (N_h \times N_{HI}) - N_{SR} \quad (5)$$

where N_h , N_{HI} , and N_{SR} represent the normalized DEM, hypsometric integral, and surface roughness values.

In their study, Lee et al. (1990) tested fractal dimension-based surface roughness under both field and laboratory conditions. The results revealed a strong correlation between surface roughness and fractal dimensions, with higher fractal dimensions corresponding to rougher terrains.

Our research conducted a correlation analysis between surface roughness and the fractal dimensions of the selected isobase surfaces. Following normalization of the fractal dimension rasters, we modified formula (5) by substitution.

$$SI_M = (N_h \times N_{HI}) - N_{FD} \quad (6)$$

Positive SI values indicate elevated surfaces with low local relief, whereas negative SI values indicate rugged landscapes (Domínguez-González et al., 2015).

The hypsometric integral (HI) effectively highlights topographic scarps, while the surface index (SI) emphasizes elevated low-relief landscapes (Andreani & Gloaguen, 2016).

Results and Discussion

After applying the hydrologic GIS algorithm to the ALOS DEM to extract stream orders, we generated 11 stream orders. Excluding the first two orders, we interpolated the elevation vertices of the remaining nine stream orders to create nine distinct isobase areas (refer to Figure 4).

Isobase number 9 was omitted from the analysis due to spatial limitations at the elevation vertices of the 11th-order grid, particularly along the Litani River. These spatial constraints made surface interpolation unfeasible.

Figure 4 displays successive isobase plots depicting the terrain surface derived from the ALOS DEM. Figure 4a spans an elevation range from 0 to 3113, representing the highest points on Lebanon's Qornet Es Sawda Mountain; figures 4b, 4c, and 4d exhibit similar elevation intervals. However, isobases 4, 5, 6, 7, and 8, which show decreasing elevation intervals, effectively illustrate the landscape evolution as presented in Table 2, showcasing the various landforms and their corresponding elevation values.

The successive isobase surfaces illustrate a notable transition from rugged to smoother terrain in a visual analysis. This transformation begins with isobase five and culminates with isobase eight. It reflects significant terrain evolution characterized by the gradual disappearance of the Lebanese western mountain range. This change is accompanied by a pronounced reduction in relative relief, as evidenced by the height-interval differences between isobases five and eight.

Table 2 presents summary statistics of elevations for each isobase area. It is important to note that surface interpolations affect the minimum elevation values across all isobase areas and do not indicate sea-level rise. The mean elevation values show a clear decrease from isobase 1 to isobase 8, effectively illustrating the landscape's evolution and the differences in elevation between these surfaces.

Isobases 1, 2, and 3 have the same minimum and maximum elevation values, though there are some differences in the mean elevation. These areas show relatively minor landscape evolution.

Conversely, a significant elevation range of 1391 meters between isobase 4 and isobase 8 indicates a substantial landscape evolution.

Although dating and correlating geological episodes that explain variation in landscape evolution across isobases is challenging, these episodes can be compared to the stages of Davis and Penck through geomorphometric analysis.

The visual analysis of the isobases in Figure 4, combined with the elevation data in Table 1, suggests similar isobase surfaces and notable landscape evolution. To distinguish isobase areas, we used a Pearson correlation matrix to compare landscapes with low versus high evolutionary rates, gaining deeper insights into landscape evolution.

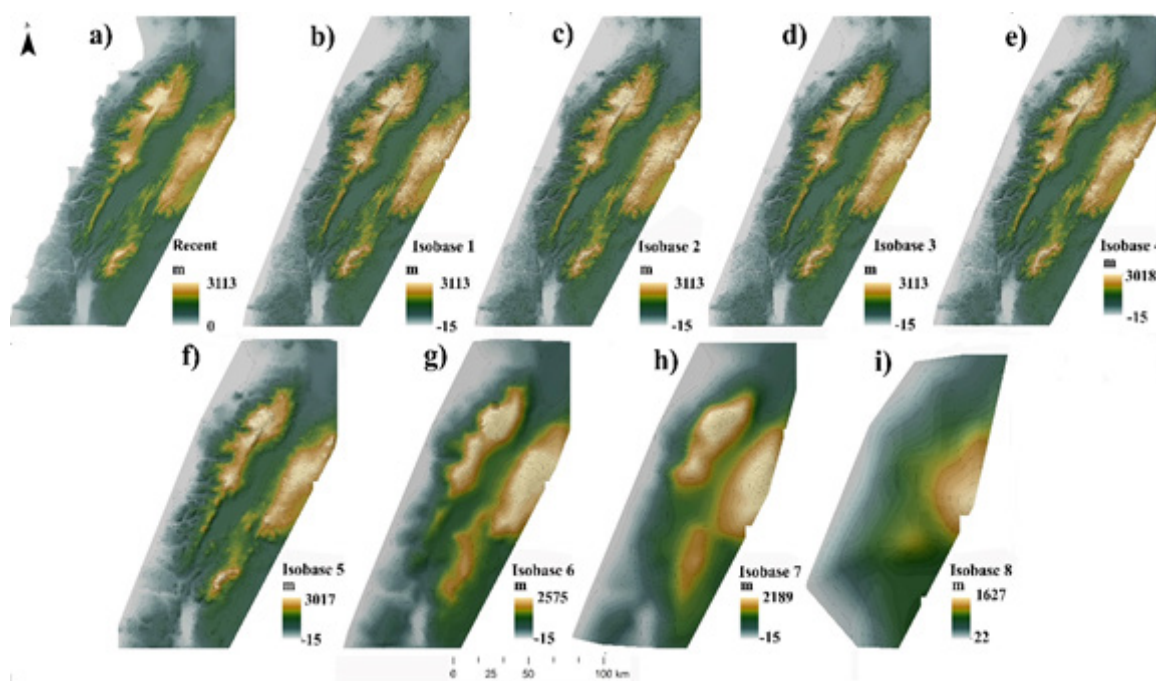


Figure 4. Landscape evolution of Lebanon's surfaces: a) recent surface, b) Isobase 1 surface, c) Isobase 2, d) Isobase 3, e) Isobase 4, f) Isobase 5, g) Isobase 6, h) Isobase 7, i) Isobase 8.

Table 2. Elevation statistics of the generated isobase surfaces, minimum, mean, maximum, and standard deviation.

	Elevations, m			
Surfaces	Minimum	Mean	Maximum	Std
Recent	0	999	3113	617
Isobase 1	-15	935	3113	643
Isobase 2	-15	936	3113	642
Isobase 3	-15	935	3113	642
Isobase 4	-15	929	3018	639
Isobase 5	-15	887	3017	619
Isobase 6	-15	818	2575	567
Isobase 7	-15	730	2189	508
Isobase 8	22	622	1627	373

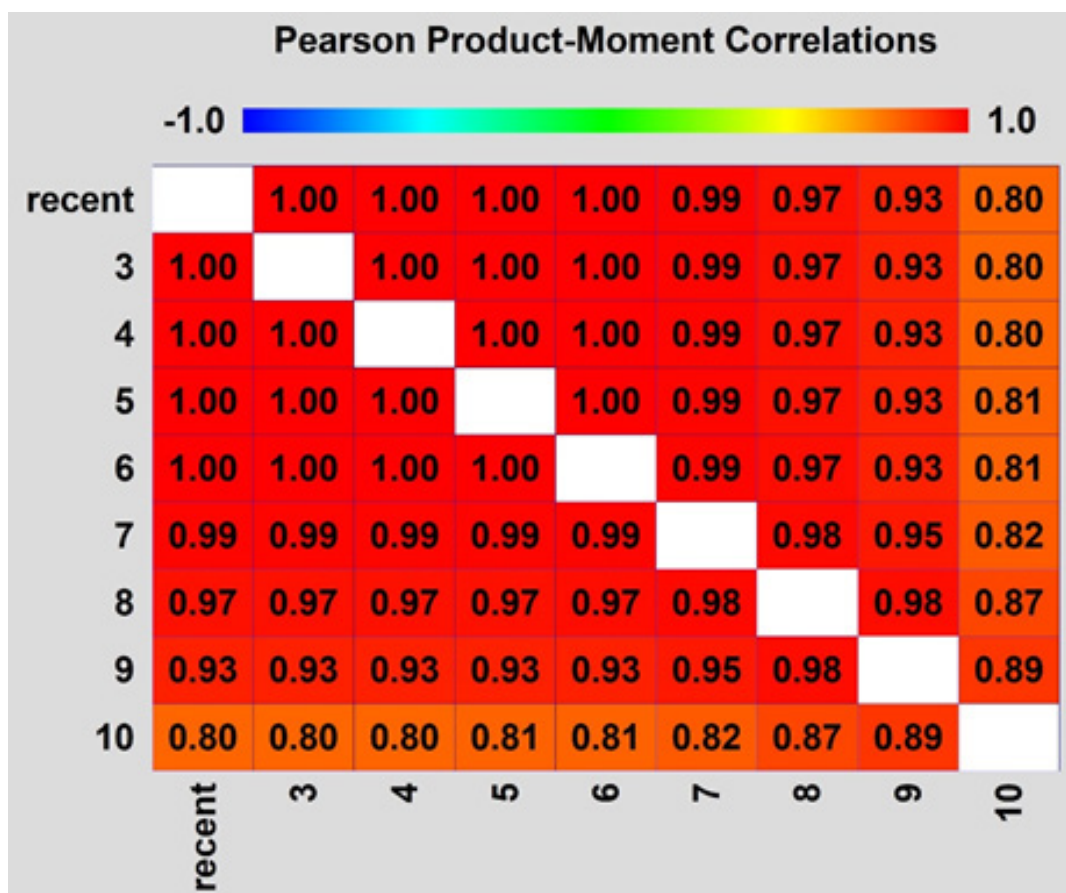
**Figure 5.** Pearson correlation matrix of isobase surfaces.

Figure 5 shows the Pearson product-moment correlations between each pair of isobase surfaces. These correlation values assess the strength of the linear relationship between the plots and demonstrate a high correlation among isobase plots 1, 2, 3, and 4, indicating low landscape development. In contrast, the correlation values decreased from 0.99 for isobase 5 to 0.8 for isobase 8, indicating high landscape development.

The youngest area (DEM) shows a strong correla-

tion with isobases 1, 2, 3, and 4, while the correlation diminishes for isobases 5, 6, 7, and 8.

Based on the visual analysis results in Figure 4, the elevation statistics in Table 2, and our correlation findings, we have excluded isobases 1, 2, 3, and 4 because they are highly similar and not relevant to landscape evolution.

Isobase plots 5, 6, 7, and 8 illustrate spatial variations in topographic and fundamental morphometric

indices, including surface profile, hypsometry, relative relief, hypsometric integral, profile curvature, fractal dimensions, and surface index, thereby enabling a comprehensive analysis of landscape evolution.

Isobase surfaces 5, 6, 7, and 8 represent hypothetical surfaces eroded to the level of the main valley floors. Contour lines (interfluvies) were generated from the DEM to construct an envelope surface connecting the highest-elevation watersheds (see Figure 6). The crests of stream order 11 were interpolated to form an under-envelope surface that links the main valley bottoms.

The Anti-Lebanon mountain range drains into the Bekaa Valley, while Mount Lebanon drains into the sea (Figure 6b). It is reasonable to expect that the equivalent uplift of the two mountain ranges would result in lower relief in the Anti-Lebanon (Gomez et al., 2006).

As shown in Figures 6a (longitudinal) and 6b (transverse), two profiles illustrate the topographical, isobase, envelope, and sub-envelope surfaces, highlighting the differences in topography and landscape evolution between Mount Lebanon and the Anti-Lebanon.

The longitudinal and transverse profiles in Figures 6a and b indicate low relief and high elevation, suggesting late Cenozoic uplift (Gomez et al., 2006). These revisions aim to improve the paragraph's clarity and coherence while preserving the accuracy of the information.

Figure 6a shows a longitudinal profile traversing the western mountainous chain of Lebanon. Conversely, Figure 6b depicts a transverse profile that crosses the western mountainous chain of Lebanon, the Bekaa Valley, and the eastern mountainous chain, showing the changes in elevation between isobases.

The longitudinal profile of the Lebanese mountain range (Figure 6a) illustrates significant landscape evolution, particularly at the summits of Qammouaa, Qornet Es Sawda, and Sannine mountains. This evolution is expressed as substantial elevation differences between the envelope and sub-envelope surfaces, referred to as relief energy (Doumit & Kiselev, 2019). The Knisse, Barrouk, Niha, and Soutaniye mountains exhibit lower relief energy.

Both the Lebanon and Anti-Lebanon mountain ranges exhibit significant topographic residuals (Figure 6), but the relief energies are more pronounced in the Lebanon Mountains compared to the Anti-Lebanon.

These disparities in relief can be attributed to differences in climate between the wetter Mount Lebanon region (with an average annual precipitation of approximately 800 mm) and the drier Anti-Lebanon region (with a mean annual precipitation of around 400 mm). Variations in base levels contribute to these differences.

While establishing precise geological ages for the generated isobase surfaces is challenging, they remain important for understanding geological history. It can be classified based on the Davis stages. Specifically,

the interval from the recent surface to isobase 5 can be considered the youth stage; isobases 6 and 7 represent maturity; isobase 8 signifies old terrain; and the sub-envelope complements this classification.

The isobase surfaces can be linked to Penck's stages: the envelope corresponds to isobase 5, which indicates the waxing or acceleration stage, while isobases 6 and 7 indicate uniform development. Additionally, isobase 8 and the sub-envelope surfaces characterize the waning or development stage.

To quantify landscape evolution and gain insights into maturity and differences between mature and less mature terrain, we developed these isobase surfaces, which provide a comprehensive comparison of geomorphological indices across the evolving landscape.

In our study, we utilized surface analysis (slope and elevation), surface hypsometry (hypsometric curves and hypsometric integrals), and terrain derivatives (profile curvature and surface index).

When discussing landscape evolution, we refer to the evolution of slopes. Davis's theory is often referred to as the slope-slope theory, and Penck's theory uses the same terminology (Davis, 1899).

The scatter plots in Figure 7 show the average slopes across eight adjacent cells along the x-axis, plotted against height above sea level on the y-axis. As indicated by ALOS DEM, the highest recorded average slope on the recent surface reaches 18 degrees, while the maximum elevation above sea level is 3113 meters. Figure 7a depicts elevated slope values within the 2400 to 2800 meters elevation range, with lower slope values at lower elevations.

Moving on to Figure 7b, which corresponds to Isobase 5, we observe a maximum elevation of 3017 meters and a maximum average slope of 13.5 degrees. Here, the youngest surface shows higher slopes at higher elevations. Figure 7c shows a decrease in slope to 0–5 degrees, alongside a reduction in elevation to 2500 meters, indicating the formation of a steeper slope. This trend continues in Isobase 7, as illustrated in Figure 7d, with an average slope of 4 degrees and an elevation of 2200 meters. Ultimately, low slope values of less than 2 degrees are reached on the surface of Isobase 8, as depicted in Figure 7e.

The scatter plots in Figure 7 clearly illustrate a proportional decrease in slope and elevation, with close similarities in their shapes. These observations, with a dynamic difference in scale, highlight the proportional nature of landscape evolution among the isobase surfaces.

To gain a more comprehensive understanding of elevation evolution, we divided all surfaces into eight intervals, as outlined in Table 3, which shows surface hypsometry and the areas corresponding to elevation intervals across the landscape-evolution surfaces.

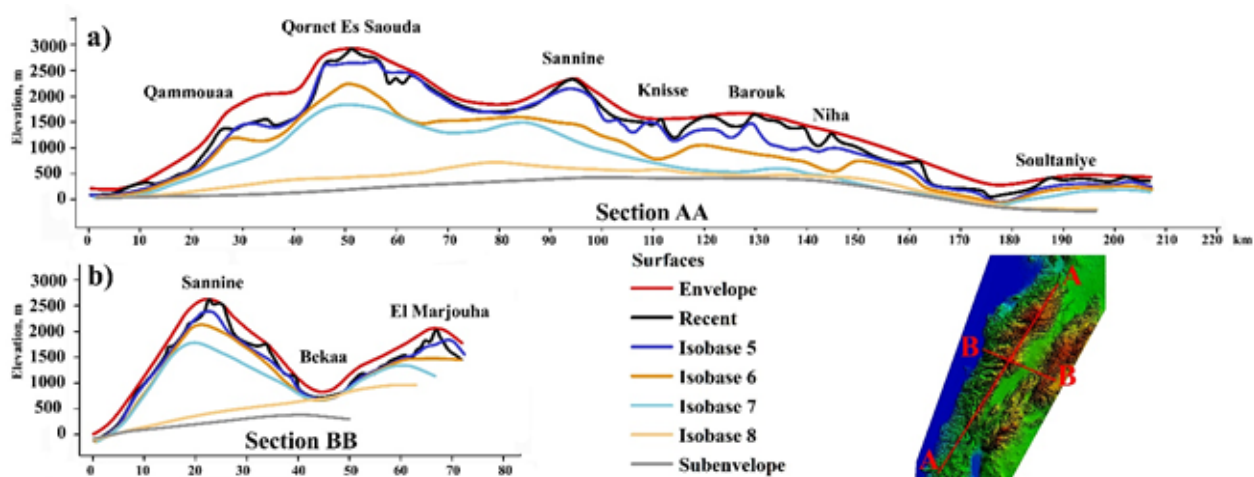


Figure 6. Illustrates the profiles of the topographic, envelope, and isobase surfaces.

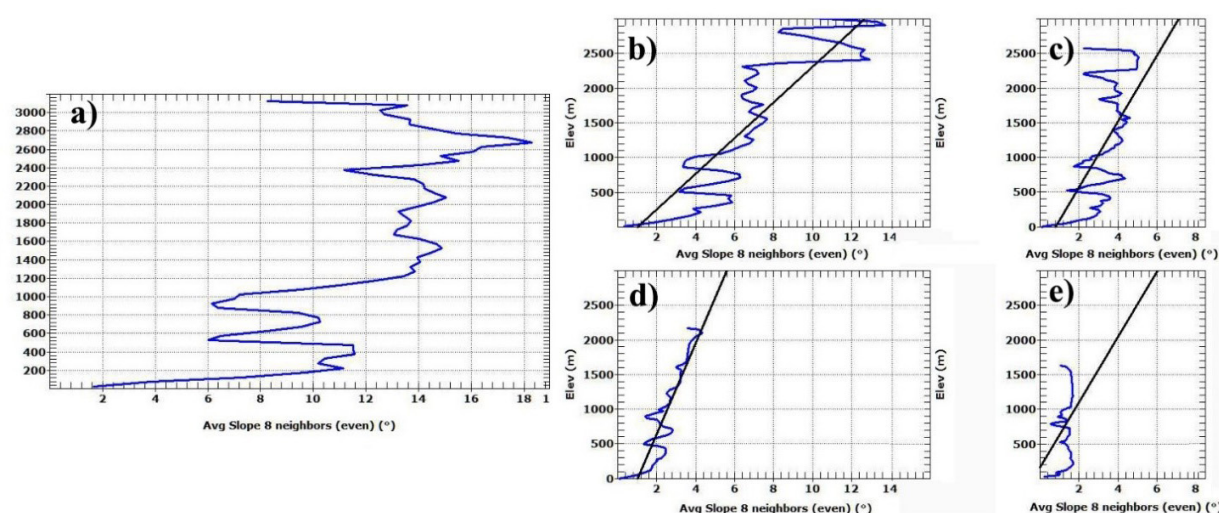


Figure 7. Scatter plot of slopes and average elevations: a) recent surface, b) isobase 5, c) isobase 6, d) isobase 7, and e) isobase 8.

Table 3. Percentage of areas corresponding to elevation intervals.

Elevation intervals, area percentages								
Surfaces	0-100	100-250	250-500	500-750	750-1000	1000-1500	1500-2000	> 2000
Recent	20	22	4	6	6	9	5	29
Isobase 5	8	9	14	20	19	3	17	11
Isobase 6	12	13	20	22	3	4	20	6
Isobase 7	9	12	16	15	17	3	13	15
Isobase 8	15	20	29	3	5	3	24	0

On the younger surface, the percentage of elevations is highest in the interval above 2000 meters, indicating that 29 percent of the Lebanese territory experienced significant uplift. The decrease in the percentage of surface area above 2000 meters for isobases 5 and 6 is attributed to pronounced erosion, while the rapid increase in surface area for isobase 7 suggests potential for uplift or sedimentary movement.

During the old stage or the declining development of isobase 8, Table 3 shows a low percentage of areas within the 500–1500-meter interval due to extensive

erosion. This results in a high percentage of areas within the 100–500-meter interval, indicating substantial sedimentation movements.

The considerable variation in surface percentages across all elevation intervals underscores the simultaneous occurrence of tectonic movements and erosional processes of varying magnitudes.

The hypsometric curve in Figure 8 shows a continuous relationship between relative elevation and the percentage of the hypsometric curve.

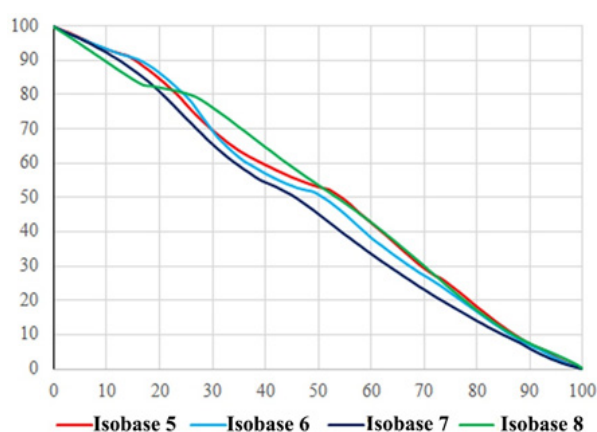


Figure 8. The hypsometric curve of Isobase surfaces.

On isobases 5, 6, and 7, the curve shape varies approximately in proportion to relative relief and area, indicating equilibrium landscape development. However, the curved shape of isobase 8, characterized by an inflection point, signifies a state of disequilibrium associated with an older stage. Relative relief was computed using Equation 1 within a 3 x 3 matrix, utilizing data from the ALOS DEM for the recent area and from the generated isobase areas 5, 6, 7, and 8.

Table 4. Minimum, mean, maximum, and standard deviation of relative relief for the recent and isobase surfaces.

Surfaces	Minimum	Mean	Maximum	Std
Recent	0	104	599	79
Isobase 5	0	46	273	39
Isobase 6	0	29	152	20
Isobase 7	0	21	100	15
Isobase 8	0	11	23	5

The theories proposed by Davis and Penck analyze the development of absolute and relative relief at various stages of landscape evolution. According to Davis, absolute relief remains relatively constant in the juvenile stage, reflecting the erosion process following uplift. However, Penck suggests that absolute relief increases during this stage, attributed to the simultaneous processes of erosion and uplift (Penck, 1953). This stage can be unpredictable because the terrain model for the surface before the youngest one is poorly documented.

Both theories agree that the juvenile stage is characterized by increased relative relief, as shown in Table 4, which reports a wide elevation range of 0 to 599 meters on the recent surface.

Moving to the mature stage, Davis asserts that absolute relief decreases, leading to valley deepening and uplift, a pattern consistent across isobases 4, 5, 6, 7, and 8 in Table 2. Penck suggests that relative relief remains stable during this stage, while absolute relief stays nearly constant.

Table 2 also shows constant absolute relief (maximum elevation) for isobases 1, 2, and 3, indicating constant relative relief, as predicted by Davis' theory. However, according to Penck's theory, the declining phase of development begins in the youngest area and extends to isobases 1, 2, and 3.

Regarding the old stage, both Davis and Penck agree that absolute and relative relief decrease directly (Davis, 1899; Penck, 1953). Relative relief values diminished with isobases 5, 6, 7, and 8.

Fractal dimension values of a surface can range from 2 for flat, smooth surfaces to 3 for very complex, rugged surfaces. The fractal dimensions of the recent and isobase surfaces were calculated using Equation 2.

Figure 9 presents a map of the fractal dimensions of the isolated surfaces, highlighting regions of extreme slope and terrain complexity. In Figure 9a, the recent surface is highly complex in areas with significant relative relief, such as the Yammounh fault and deep river valleys, with fractal dimensions ranging from 2.02 to 2.04. These areas are elevated and heavily eroded due to substantial topographic differences.

The lowest fractal dimension values (2) are found in the isobase regions 5 and 6 in the Beqaa Valley, particularly in the Amiq area (i.e., low-amplitude landscapes).

Figure 9b of isobase 5 shows a stretched interval of values ranging from 2 flat-surface amplitudes to 2.4 high-elevation amplitudes along the Yammounh fault, the Ibrahim River, and the Qadisha River valleys.

As the landscape evolves from Isobase 6 to Isobase 8, the fractal dimension decreases, and the terrain becomes smoother rather than flat.

During this period, landform inversion may occur; that is, slopes may initially have convex profiles (Figure 6), then become concave, and, at a later stage, become convex again, particularly if depositional material is involved (Moss, 1977).

Profile curvature measures the curvature of each isobase surface to better illustrate slope development.

Table 5. Profile curvature types and the percentage of the area

Profile Curvature (PC) area%			
Surface	Concave	Straight	Convex
Recent	16	51	32
Isobase 5	28	31	41
Isobase 6	45	20	35
Isobase 7	11	37	52
Isobase 8	10	58	32

Table 5 summarizes the percentages of areas with concave, straight, and convex profile curvature on the isobase surfaces. In isobase 5, the hillside displays a convex slope before significant water-related development, indicating a high percentage of convex areas influenced by gravitational processes.

As water's influence increases, the slope gradually becomes concave. In isobase 6, the concave shape balances convex and concave slopes, resulting in a gravitational wash effect. The deep weathering of isobase 7 surfaces creates a convex slope, with a significant 52% of the area occupied by convex features.

The slope dynamics are at play in isobase 8, characterized by high landscape evolution and rapid forces of change (Coates, 1984). Penck (1953) mentions in his theory that during the decreasing or developmental phase, gravity processes dominate in the upper range (in our case, isobase 6) while washing tendencies prevail in the lower range (isobase 7).

The hypsometric integral, calculated using equation 4, provides insights into the erosion stage and the factors influencing it, such as tectonic, climatic, and lithologic factors. Low hypsometric integral values, close to 0, indicate older, highly dissected areas. In contrast, high values near 1 indicate regions with high relative relief, such as smooth upland surfaces intersected by deep rivers, as in the valleys of the Ibrahim and Abou Ali rivers, which are indicative of younger, less-eroded areas (Sarp et al., 2011).

The hypsometric integral maps of the isobase surfaces (Figure 10) predominantly reflect tectonic features. The highest values are concentrated along the Lebanon and Anti-Lebanon mountain ranges, while the lowest values are observed in depressions and in areas of the Beqaa Valley.

The Hypsometric Integral (HI) values range from 0 to 0.99, with lower values typically observed in depressions and higher values at the crests of uplifted regions. Specifically, in the recent isobase 5 and 6 surfaces, the high and low HI values fall within the intervals of 0.58–0.99 and 0–0.42, respectively.

However, on isobase surfaces 7 and 8, as shown in Figures 10d and 10e, the high-value interval vanishes, indicating the disappearance of young, less eroded areas. The older and more eroded regions now fall within the HI range of 0–0.42.

This outcome suggests that young, less-eroded areas become increasingly scarce during the waning or developmental stage.

To discriminate low terrain based on elevations, we employed the modified Surface Index (SI) as defined in equation 6. The calculated SI for the recent surface ranges from -0.92 to 0.68, with a few negative values observed in the V-shaped river valleys.

The disparities in landscape evolution are likely attributable to factors such as tectonic processes, erodibility, weathering, and landscape aging resulting from fluvial erosion, hillslope diffusion, and uplift.

- Penck (1953), in his theory, mentions that in the waning or development stage, the gravity produced is in the upper region, in our case, and based on profile curvature, results in the gravity produced in isobase 6 and the wash slope of the lower region in isobase 7.

- From the Hypsometric integral result, in the waning or development stage, young and less eroded areas disappeared.
- The Surface Index in the evolution stage of isobases 8 and 9 highlights the appearance of three zones: a high dissected low-elevation zone, a moderately dissected hilly zone, and a third low dissected high-elevation zone. These zones may be associated with the End Rumpf stage.
- Prediction of the landscape evolution map of Lebanon-based isobase surfaces.

SI maps (Figure 11) highlight areas of low terrain amplitude, surrounded by more dissected complex landforms with high roughness, as indicated by fractal dimensions. Figure 11 illustrates the dual-terrain distribution, with positive values indicating elevated relief and negative values denoting dissected low relief.

SI is a measure of erosion: areas with low fractal dimensions yield positive SI values, whereas highly dissected terrain with high fractal dimension yields negative SI values. In recent surface, SI values range from -0.92 to 0.68, with negative values associated with highly dissected areas, such as V-shaped valleys.

Both the Lebanon and Anti-Lebanon mountainous chains exhibit positive surface indices, with higher values observed on their crests. Figure 11a delineates a transition belt from negative to positive SI values, dividing Lebanon into two regions: Eastern tectonic uplifted areas and Western erosion-prone areas. This transition belt becomes more complex in isobases 5 and 6 (Figures 11b and 11c), and the lower SI interval (-0.92 to 0.05) widens across the Ibrahim River valley and the higher lands of the Abou Ali River basin.

On the isobase surface 7, the transition belt assumes a smoother form, connecting Lebanon and the Anti-Lebanon Mountains and encircling the Beqaa Valley. In the western part, dissection intensifies in the Ibrahim and Abou Ali watersheds (Figure 11d).

In the landscape evolution stage of isobase 8 (Figure 11e), three zones emerge: a highly dissected low-elevation zone (the coastal area), a moderately dissected hilly zone in the middle and south of the study area, and a third low-dissected high-elevation zone to the east. This result allows us to relate isobase 8 and isobase 9 to the End Rumpf landscape evolution stage (slopes backwashing) of Penck, which depends on uplift and erosion.

Landscape assessment involves mapping the residual topography of the recent surface by subtracting isobase 5 from isobase 6 to form topographic surface A, subtracting isobase 6 from isobase 7 to form surface B, and subtracting isobase 7 from isobase 8 to create topographic surface C (Filosofov, 1975). These three topographic residual surfaces depict terrain fluvial incision, influenced by factors such as tectonic activity, isobase surface variations, lithology, vegetation, and climate (Gomez et al., 2006). These factors collectively

contribute to the Landscape evolution map of Lebanon in Figure 12.

The predicted landscape evolution map of Lebanon (Figure 12) aligns with the profiles in Figure 6, highlighting areas of high- to low-evolution during the erosion cycle and categorized into five stages. Stage one represents the initial development episode, encompassing the evolution of the Lebanon mountainous chain, including Qornet Es Sawda, Sannine, Barouk, Knise, and some isolated hills. The final stage of the evolution map corresponds to older river terraces, formed by vertical erosion of streams into their depositional floodplains. This stage exhibits terraces at different heights, indicative of former riverbed levels, particularly along the Abou Ali and Ibrahim rivers.

The results of morphometrical analysis of the isobase surfaces reveal several key findings:

- The decrease in slope and elevation is proportional to landscape evolution between isobase surfaces.
- The variation in isobase surfaces' elevation intervals confirms varying degrees of simultaneous tectonic movements and erosion processes.

Hypsometric curves indicate equilibrium in landscape evolution on isobase surfaces 5 and 6, but an imbalance in the evolution of the older stage isobase surfaces 8 and 9.

- Relative relief results suggest that, according to Davis's theory, the mature stage begins with isobase surface 4, whereas, following Penck's theory, waning development initiates with the recent surface and continues in Isobases 1, 2, and 3.

- For the old stage, both Davis's and Planck's theories concur that absolute and relative relief decrease directly, with relative relief values declining in isobases 5, 6, 7, and 8.

- Fractal dimensions decrease, and the terrain becomes smoother, though not flat, as landscape evolution progresses from isobase 6 to isobase 8.

Based on the experimental results, Penck's theory is better suited to the landscape evolution of the Lebanese terrain. The recent evolution stage is the waning or development stage, with no further uplift, gravity, or wash slopes.

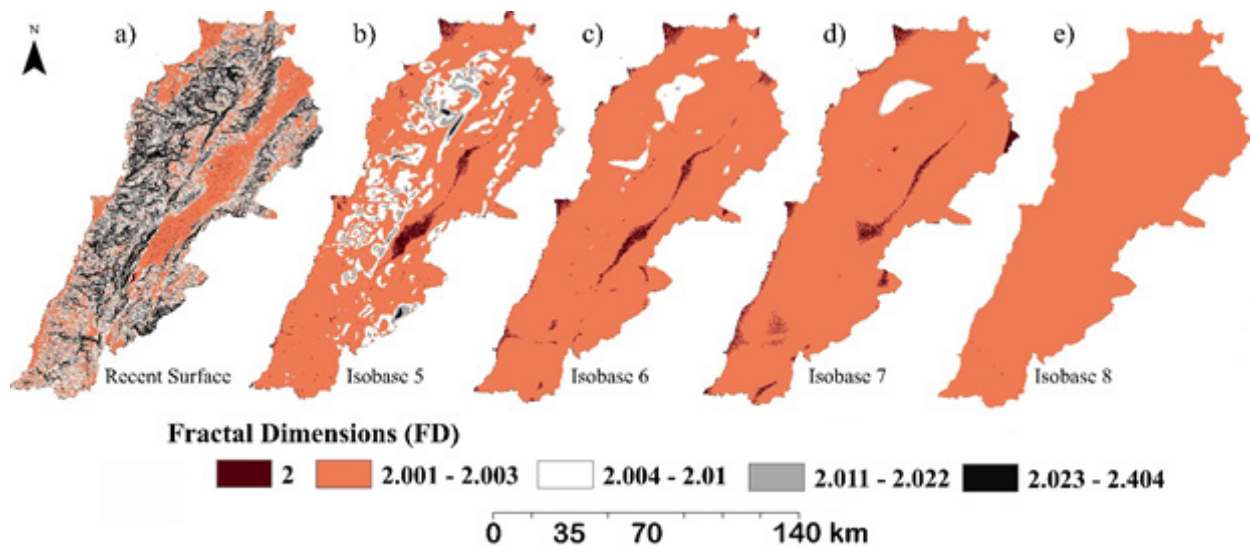


Figure 9. Fractal dimensions maps: a) recent surface, b) isobase 5, c) isobase 6, d) isobase 7, and e) isobase 8.

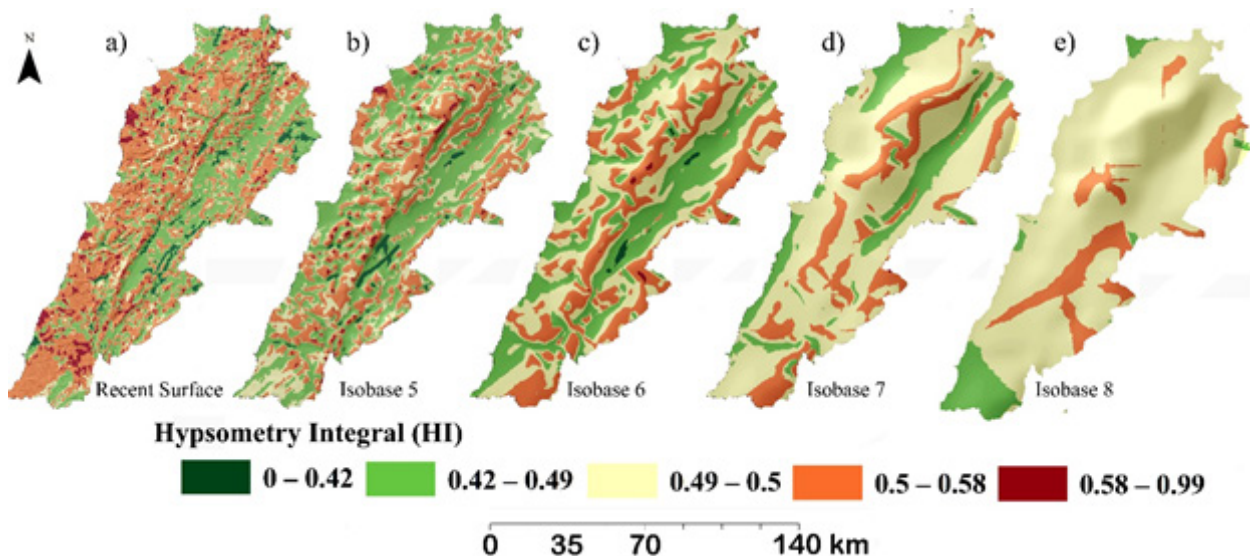


Figure 10. Hypsometric integral maps: a) recent surface, b) isobase 5, c) isobase 6, d) isobase 7, and e) isobase 8.

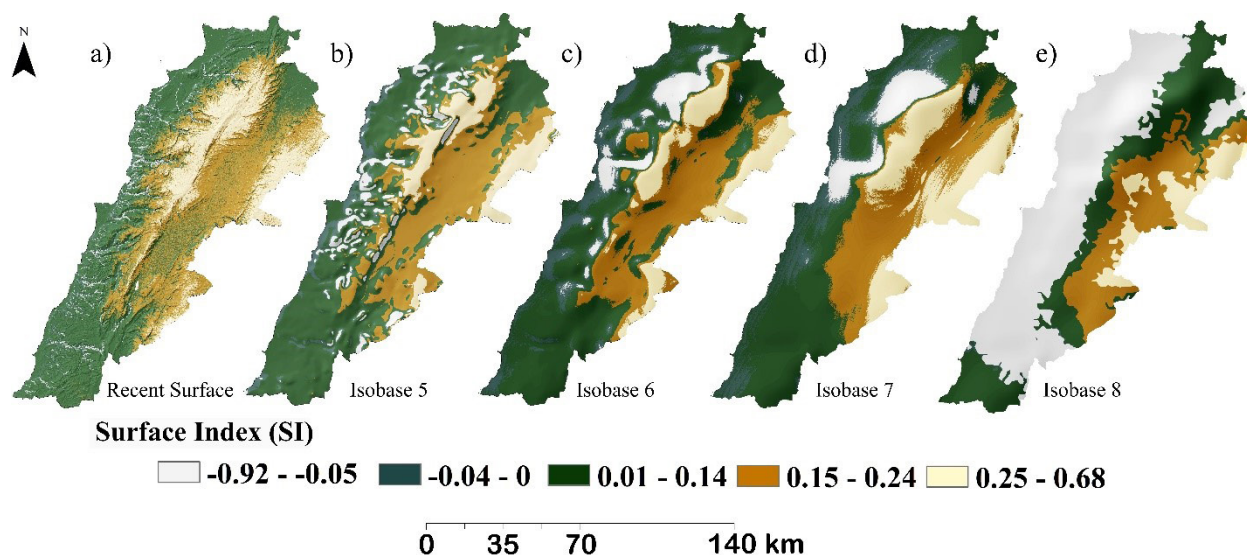


Figure 11. Surface index maps: a) recent surface, b) isobase 5, c) isobase 6, d) isobase 7, and e) isobase 8.

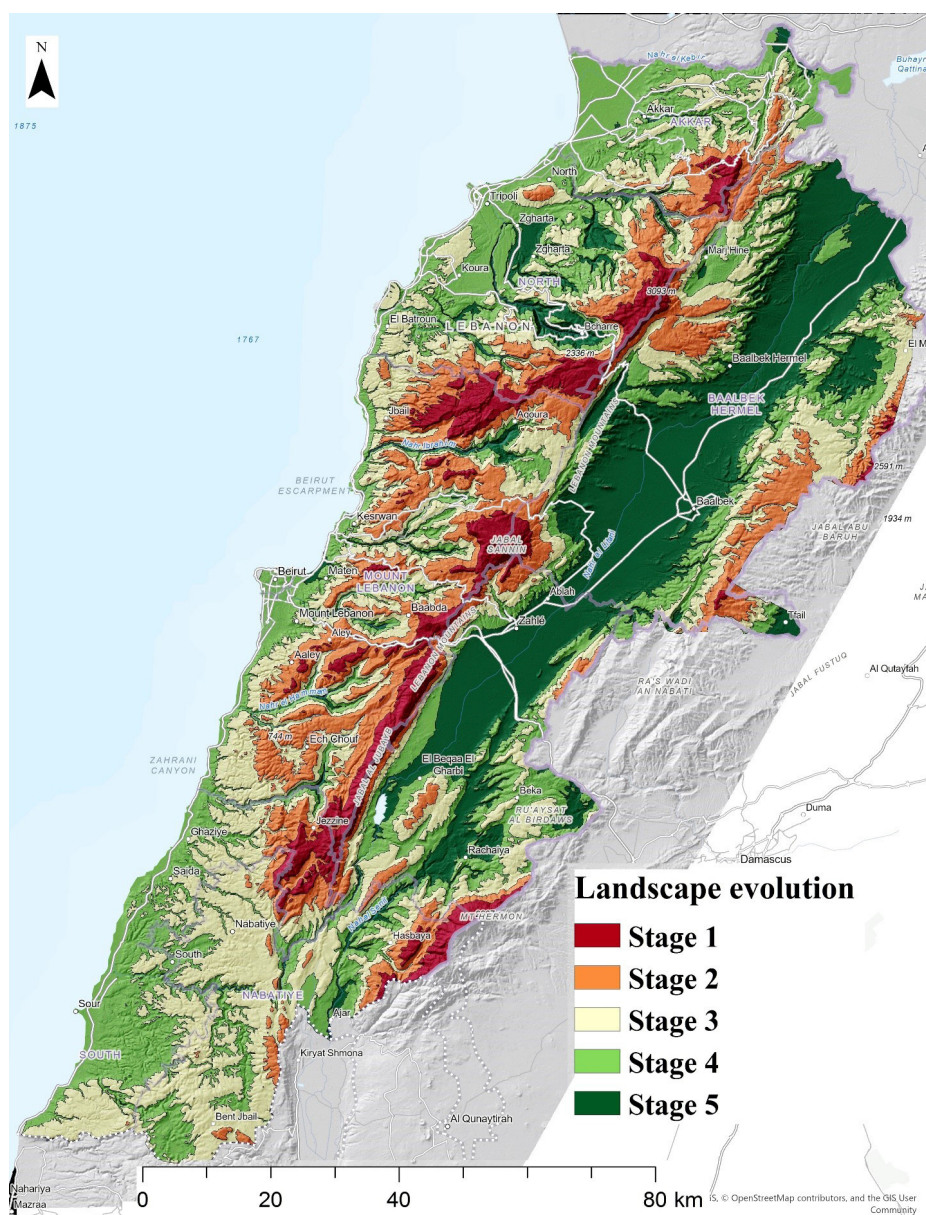


Figure 12. Landscape evolution map of Lebanon.

Conclusion

In our experiment, we aimed to comprehensively analyze landscape evolution. We used DEM and GIS tools to generate stream-order networks, construct isobase surfaces, and calculate geomorphometric indices. The analysis delineated distinct terrain patterns, shedding light on various tectonic and erosional stages.

We employed methods including topographic profiles, hypsometric curves, and morphometric maps applied to isobase surfaces of stream orders to gain insights into the spatial distribution of landscape evolution. The results of our geomorphometric analysis provided valuable insights, enabling us to link landscape evolution in Lebanon to Penck's theory.

It is important to note that our analysis focused exclusively on physiographic landscape forms to predict landscape evolution and was not directly linked to geological or tectonic studies. Instead, it introduced a nov-

el approach that could complement future geological and tectonic analyses of the study area.

Based on our findings and applying Penck's theory, we propose a new hypothesis: both the waxing (accelerating) and uniform development stages have occurred, and we are currently in the waning (development) stage. The recent Lebanese terrain and isobases 1, 2, 3, and 4 are at the peak of the waning (mature) stage. Successive isobases 5, 6, and 7 mark the end of the waning development stage and the beginning of the old age stage. Isobases 8 and 9 represent the End Rumpf stage.

This experiment enhances our understanding of landscape evolution in Lebanon and underscores the potential of geomorphometric analysis to offer valuable insights into complex geological processes.

References

- Andreani, L., Stanek, K. P., Gloaguen, R., Krentz, O., & Domínguez-González, L. (2014). DEM-based analysis of interactions between tectonics and landscapes in the Ore Mountains and Eger Rift (East Germany and NW Czech Republic). *Remote Sensing*, 6(9), 7971–8001.
- Andreani, L., & Gloaguen, R. (2016). Geomorphic analysis of transient landscapes in the Sierra Madre de Chiapas and Maya Mountains (northern Central America): Implications for the North American–Caribbean–Cocos plate boundary. *Earth Surface Dynamics*, 4, 71–102. <https://doi.org/10.5194/esurf-4-71-2016>
- Burt, T. P., Chorley, R. J., Brunsdon, D., Cox, N. J., & Goudie, A. S. (Eds.). (2008). *The history of the study of landforms* (Vol. 4). The Geological Society.
- Coates, D. R. (1984). Landforms and landscapes as measures of relative time. In *Quaternary dating methods* (pp. 247–267). [https://doi.org/10.1016/S0920-5446\(08\)70075-X](https://doi.org/10.1016/S0920-5446(08)70075-X)
- Crickmay, C. H. (1974). *The work of the river: A critical study of the central aspects of geomorphology*. American Elsevier Publishing Company.
- Davis, W. M. (1889). The rivers and valleys of Pennsylvania. *National Geographic Magazine*, 1, 183–253.
- Davis, W. M. (1899). The geographical cycle. *The Geographical Journal*, 14(5), 481–504. <https://doi.org/10.2307/1774538>
- Davis, W. M. (1905). Complications of the geographical cycle. In *Eighth International Geographical Congress, Washington, 1904* (pp. 150–163).
- Davis, W. M. (1909). *Geographical essays* (D. W. Johnson, Ed.). Ginn and Company.
- Domínguez-González, L., Andreani, L., Stanek, K. P., & Gloaguen, R. (2015). Geomorphotectonic evolution of the Jamaican restraining bend. *Geomorphology*, 228, 320–334. <https://doi.org/10.1016/j.geomorph.2014.09.019>
- Doumit, J. A. (2017). *Digital terrain analysis of Lebanon: A study of geomorphometry*. Scientific Edition Polygraph Center, Kuban State University.
- Doumit, J. A., & Kiselev, E. N. (2019). The quantitative approach of relative height and microrelief: Three case studies from Lebanon. In *Science and practice solutions: Strategic and tactical tasks of sustainable development of Russia* (pp. 16–19).
- Dubertret, L. (1934). Présentation d'une carte géologique générale au 1:1 000 000 de la Syrie et du Liban. *Revue de Géographie Physique et de Géologie Dynamique*, 6(4), 269–318.
- Dubertret, L. (1947). Aperçu de géographie physique sur le Liban, l'Anti-Liban et la Damascène. *Notes et Mémoires*, 4, 191–226.
- Dury, G. H. (1952). *Map interpretation*. Edward Arnold.
- Evans, I. S. (1980). An integrated system of terrain analysis and slope mapping. *Zeitschrift für Geomorphologie, Neue Folge, Supplementband*, 36, 274–295.
- Filosofov, V. P. (1960). *A brief guide to morphometric methods in search of tectonic structures*. Saratov University Publishing House. [In Russian]

- Filosofov, V. P. (1970). Maps of isobases and residual relief. In *Application of geomorphic methods in structural investigations* (pp. 43–52). NEDRA. [In Russian]
- Filosofov, V. P. (1975). *The basis of the morphometric method in search of tectonic structures*. Saratov University Publishing House. [In Russian]
- Florinsky, I. V. (2012). Digital elevation models. In *Digital terrain analysis in soil science and geology* (pp. 1–25). Academic Press. <https://doi.org/10.1016/B978-0-12-385036-2.00003-1>
- Gary, M., McAfee, R., Jr., & Wolf, C. L. (Eds.). (1973). *Glossary of geology* (2nd ed.). American Geological Institute.
- Golts, S., & Rosenthal, E. (1993). A morphotectonic map of the northern Arava in Israel, derived from isobase lines. *Geomorphology*, 7, 305–315. [https://doi.org/10.1016/0169-555X\(93\)90060-F](https://doi.org/10.1016/0169-555X(93)90060-F)
- Gomez, F., Khawlie, M., Tabet, C., Darkal, A. N., Khair, K., & Barazangi, M. (2006). Late Cenozoic uplift along the northern Dead Sea Transform in Lebanon and Syria. *Earth and Planetary Science Letters*, 241, 913–931. <https://doi.org/10.1016/j.epsl.2005.10.029>
- Gravelius, H. (1914). *Flusskunde*. G. J. Göschen'sche Verlagshandlung.
- Grohmann, C. H., Riccomini, C., & Alves, F. M. (2007). SRTM-based morphotectonic analysis of the Poços de Caldas Alkaline Massif, southeastern Brazil. *Computers & Geosciences*, 33(1).
- Grohmann, C. H., Riccomini, C., & Chamani, M. A. C. (2011). Regional-scale analysis of landform configuration with base-level (isobase) maps. *Hydrology and Earth System Sciences*, 15, 1493–1504. <https://doi.org/10.5194/hess-15-1493-2011>
- Hack, J. T. (1960). Interpretation of erosional topography in humid temperate regions. *American Journal of Science*, 258-A, 80–97.
- Hamood, R. R. (2009). The cycle of erosion was proposed in Davis and Penck's comparative study. *Al-Fatih Journal*, 5(38), 65–79.
- Horton, R. E. (1945). Erosional development of streams and their drainage basins: Hydrophysical approach to quantitative morphology. *Geological Society of America Bulletin*, 56(3), 275–370. [https://doi.org/10.1130/0016-7606\(1945\)56%5B275:E-DOSAT%5D2.0.CO;2](https://doi.org/10.1130/0016-7606(1945)56%5B275:E-DOSAT%5D2.0.CO;2)
- Keller, E. A., & Pinter, N. (1996). *Active tectonics: Earthquakes, uplift, and landscape*. Prentice Hall.
- King, L. C. (1953). Canons of landscape evolution. *Geological Society of America Bulletin*, 64(7), 721–752. [https://doi.org/10.1130/0016-7606\(1953\)64%5B721:COLE%5D2.0.CO;2](https://doi.org/10.1130/0016-7606(1953)64%5B721:COLE%5D2.0.CO;2)
- Lee, Y. H., Carr, J. R., Barr, D. J., & Haas, C. J. (1990). The fractal dimension as a measure of the roughness of rock discontinuity profiles. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 27(6), 453–464. [https://doi.org/10.1016/0148-9062\(90\)90998-H](https://doi.org/10.1016/0148-9062(90)90998-H)
- Logan, T. A., Nicoll, J., Laurencelle, J., Hogenson, K., Gens, R., Buechler, B., Barton, B., Shreve, W., Stern, T., Drew, L., & Guritz, R. (2014, December). Radiometrically terrain-corrected ALOS PALSAR data available from the Alaska Satellite Facility [Conference presentation abstract]. *American Geophysical Union Fall Meeting 2014*.
- Mahmood, S. A., & Gloaguen, R. (2012). Appraisal of active tectonics in Hindu Kush: Insights from DEM-derived geomorphic indices and drainage analysis. *Geoscience Frontiers*, 3, 407–428. <https://doi.org/10.1016/j.gsf.2011.12.002>
- Mandelbrot, B. B. (1982). *The fractal geometry of nature*. W. H. Freeman.
- Moss, J. H. (1977). The formation of pediments: Scarp back wearing or surface down wasting. In D. O. Doehring (Ed.), *Geomorphology of arid regions* (pp. 51–78). State University of New York.
- Pannekoek, A. F. (1967). Generalized contour maps, summit level maps and streamline surface maps as geomorphological tools. *Zeitschrift für Geomorphologie*, 11, 169–182.
- Penck, W. (1953). *Morphological analysis of landforms* (H. Czech & K. C. Boswell, Trans. & Eds.). Macmillan.
- Pike, R. J., & Wilson, S. E. (1971). Elevation-relief ratio, hypsometric integral, and geomorphic area-altitude analysis. *Geological Society of America Bulletin*, 82(4), 1079–1084. [https://doi.org/10.1130/0016-7606\(1971\)82%5B1079:ERHIAG%5D2.0.CO;2](https://doi.org/10.1130/0016-7606(1971)82%5B1079:ERHIAG%5D2.0.CO;2)
- Sarp, G., Toprak, V., & Düzgün, Ş. (2011). Hypsometric properties of the hydrologic basins located on the western part of NAFZ. In *Proceedings of the 34th International Symposium on Remote Sensing of Environment*. Sydney, Australia.
- Scotti, V. N., Molin, P., Faccenna, C., Soligo, M., & Casas-Sainz, A. (2014). The influence of surface and tectonic processes on landscape evolution

- of the Iberian Chain (Spain): Quantitative geomorphological analysis and geochronology. *Geomorphology*, 206, 37–57. <https://doi.org/10.1016/j.geomorph.2013.09.017>
- Strahler, A. N. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Geological Society of America Bulletin*, 63(11), 1117–1142. [https://doi.org/10.1130/0016-7606\(1952\)63%5B1117:HAAOET%5D2.0.CO;2](https://doi.org/10.1130/0016-7606(1952)63%5B1117:HAAOET%5D2.0.CO;2)
- Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union*, 38(6), 913–920. <https://doi.org/10.1029/TR038i006p00913>
- Summerfield, M. A. (1991). *Global geomorphology*. Longman Scientific & Technical.
- Vasconcelos, P. M., & Carmo, I. de O. (2018). Calibrating denudation chronology through $^{40}\text{Ar}/^{39}\text{Ar}$ weathering geochronology. *Earth-Science Reviews*, 179, 411–435. <https://doi.org/10.1016/j.earscirev.2018.01.003>
- Von Engel, O. D. (1960). *Geomorphology*. The Macmillan Company.
- Walley, C. D. (1998). *The geology of Lebanon*. American University of Beirut.
- Worchester, P. G. (1958). *Textbook of geomorphology*. D. Van Nostrand Company.
- Zevenbergen, L. W., & Thorne, C. R. (1987). Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, 12, 47–56. <https://doi.org/10.1002/esp.3290120107>