

Article

A Hypsometric-Energetic Framework for Identifying Gully-Initiation Belts in Low-Permeability Catchments

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Abstract

The formation and development of gullies are pervasive drivers of hillslope degradation, yet forecasting where and at what elevation gullies begin remains challenging. This study proposes a morphometric–energetic framework to anticipate gully-initiation zones in catchments developed on low-permeability lithologies and limited tectonic control across contrasting climatic and geomorphic settings. Using GIS analyses and morphometric parameters, with some derived from hypsometric curves, our objective is to link basin-scale morphology and energy distribution to the propensity for linear incision, thereby defining a statistically representative initiation belt and stream network positions most susceptible to gully initiation. The study results show that the altitudinal range most susceptible to gully development is at the mean basin’s elevation, and that this range can be associated with an energy potential (Sen’s “Energy Index”) similar to those used to calculate hydro-electric potential in a river basin. Furthermore, the study highlights that the contributing area required to activate these erosive processes varies within fairly narrow limits, between 1 and 3 ha. The framework is designed to be quantitative, transferable among landscapes, and parsimonious in data requirements, even if applicable, as mentioned, in basins with low-permeability lithology and limited tectonic control, and as a first-level predictive tool. By prioritizing diagnostics that can be computed from standard topographic datasets, the approach aims to support land-use planning and sediment-risk mitigation, offering a practical pathway for early identification and management of areas vulnerable to gullying.

Keywords: gully erosion; hypsometric curve; morphometric analysis; water energy potential

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1. Introduction

Linear erosion processes, particularly those driven by concentrated overland flow, are widely recognized as dominant mechanisms of global land degradation. These processes involve the removal of soil along preferential flow paths, leading to channel incision and the formation of rills and gullies. In the context of the Anthropocene, such erosive dynamics have intensified dramatically. This escalation is primarily attributed to the combined influence of climate change, land-use shifts (e.g., deforestation, urbanization,

and agricultural expansion), and unsustainable land management practices [1–3]. Among the various forms of linear erosion, gully erosion stands out for its severity and geomorphic impact. It represents an advanced stage of surface incision, in which ephemeral or permanent channels become deeply entrenched, often irreversibly altering the hydrological and sediment transport regimes of catchments. Gully erosion not only results in substantial topsoil loss and reduced land productivity but also poses a significant threat to downstream environments by contributing disproportionately to sediment yields. Empirical studies indicate that gully systems can contribute up to 90% or more of the total sediment load delivered by fluvial systems, especially in degraded or semi-arid landscapes [2,4–11]. This type of erosion is further exacerbated by the increasing frequency of extreme rainfall events, linked to global climate variability, which enhances runoff generation and stream power.

Despite their recognized environmental and geomorphological importance, linear erosion processes, such as rill and gully formation, have historically received significant scientific attention but yielded limited results, particularly regarding their initiation mechanisms and temporal evolution. This research gap is mainly attributable to the intrinsic complexity of these processes, which involve a broad range of interacting geomorphological, hydrological, and pedological factors. The genesis and dynamics of gully systems, in particular, are influenced by variables such as rainfall intensity, soil erodibility, slope morphology, vegetation cover, and anthropogenic disturbances. These factors are difficult to quantify and integrate into reliable predictive models. As highlighted by several authors [12–15], the lack of consistent field data, along with the spatial heterogeneity of erosion-prone areas, has posed significant challenges to model calibration and validation.

To address this complexity, morphometric analysis has emerged as one of the earliest and most robust quantitative frameworks for interpreting the form and function of drainage basins. By quantifying key metrics such as drainage density, stream frequency, bifurcation ratio, relief, and hypsometric integral, morphometric studies provide insight into catchment erosional maturity, sediment transport potential, and susceptibility to linear erosion. The foundation of this approach can be traced back to the seminal work of Horton [16,17], who pioneered the mathematical characterization of drainage networks and set the stage for the evolution of modern geomorphometry.

Subsequent advancements [18–21] significantly expanded the theoretical and methodological framework, enabling more refined assessments of basin evolution and erosional energy. These methods are now complemented by GIS and remote sensing technologies, which have revolutionized morphometric research by enabling high-resolution, spatially explicit analysis across large, inaccessible terrains.

Topographic parameters, particularly the relationship between local slope gradient (S) and drainage area (A), have proven to be key indicators in understanding the spatial initiation and development of gully erosion. Numerous studies have highlighted how this S – A relationship effectively governs the location of gully heads across a wide range of geomorphic settings, especially in hillslopes subject to diffused hydrological and erosive pressures [2,22–25]. This relationship is often expressed through threshold equations of the form $S = aA^b$, where the coefficient a and the exponent b are empirically derived and reflect local environmental conditions, such as lithology, vegetation cover, rainfall intensity, and land use [26,27]. Recent applications of this model have yielded specific threshold curves that delineate the critical conditions under which concentrated overland flow transitions into channelized erosion, providing valuable predictive insights into erosion risk mapping and landscape evolution modeling.

This study follows a previous research conducted by the same authors [28]. Using an original morphometric approach and basic GIS tools, they identified the transition between catchment sectors with different erosive capacities of running water, confirming

the Strahler [18] insight into the important geomorphological role of the inflection point of the hypsometric curve. Although many studies recognize that rainfall intensity and duration, antecedent soil moisture, soil hydraulic and mechanical properties, land use, vegetation cover, tillage practices, and local anthropogenic modifications are all known to influence gully initiation and evolution, these factors are not explicitly parameterized in the present model. The objective in the present work is therefore not to provide a complete process-based susceptibility model, but to test whether basin-scale topography alone can define a central tendency of an elevation belt where gully initiation is statistically more likely under the lithological and morphometric conditions analyzed. This choice also allows the method to be applied consistently in different geographical settings using only standard DTM-derived variables. The approach should consequently be considered a first-level screening tool to be integrated in future work with rainfall, soil, vegetation, land-use, and management data. The novelty compared to the authors' previous work, in addition to expanding the number and geomorphological–environmental context of the studied areas, lies in the introduction of a parameter that quantifies the gullies' activation energy, thereby allowing comparison between morphometric indices, hydrographic network development, and erosive potential in a hydrographic basin. This morphometric/hypsometric approach has been applied to 35 sample basins across three test areas: one in central Italy, another in the Mountain States (USA, Wyoming), and a third in New Zealand. All these basins are characterized by different climatic, morphometric, geomorphological, and land-use conditions, as well as different degrees of anthropization; the only similarities are the less permeable bedrock, which allows the formation of a well-developed hydrographic network, and the low degree of tectonic conditioning.

The study also demonstrates that the central elevation belt of gully initiation is strictly related to the basin's mean elevation and, among other things, to the relative maximum of the energy potential distributed downwards from the watershed.

2. Materials and Methods

2.1. Study Areas

In this study, as already mentioned, 35 sample basins were selected in three study areas from three different continents (North America—USA, Europe—Italy, and Oceania—New Zealand) (Figure 1). The sample basins were selected using predefined geomorphological and data-quality criteria rather than by random sampling. Selection required low permeability lithologies, clearly identifiable drainage divides, limited tectonic or structural control on the drainage network, availability of comparable DTM data, and the presence of recognizable gully heads for validation. The basins were also chosen to cover different climatic and geomorphic contexts, but no basin was selected based on the expected agreement between gully-head elevation and hypsometric or Energy Index parameters.

2.1.1. Area 1—North America

The first study area covers a sector of about 2100 km² within the Gillette coalfield in northeastern Wyoming (Figure 2a). The landscape is defined by a broad highland with gentle ridges and limited elevation differences, ranging between 1400 and 1500 m a.s.l. Human impact in the area is minimal, restricted to scattered buildings mainly located across the plains; the slopes remain largely uncultivated, with sparse vegetation (predominantly shrubs) concentrated within river valleys. The bedrock is relatively homogeneous, consisting primarily of Paleocene and Eocene siltstones and shales, locally overlain by weathered silty-clay deposits (especially on hilltops and ridges) or fine colluvium [29,30].

Stratigraphically, these formations exhibit a highly regular structure, with nearly continuous horizontal layers and little to no tectonic influence.

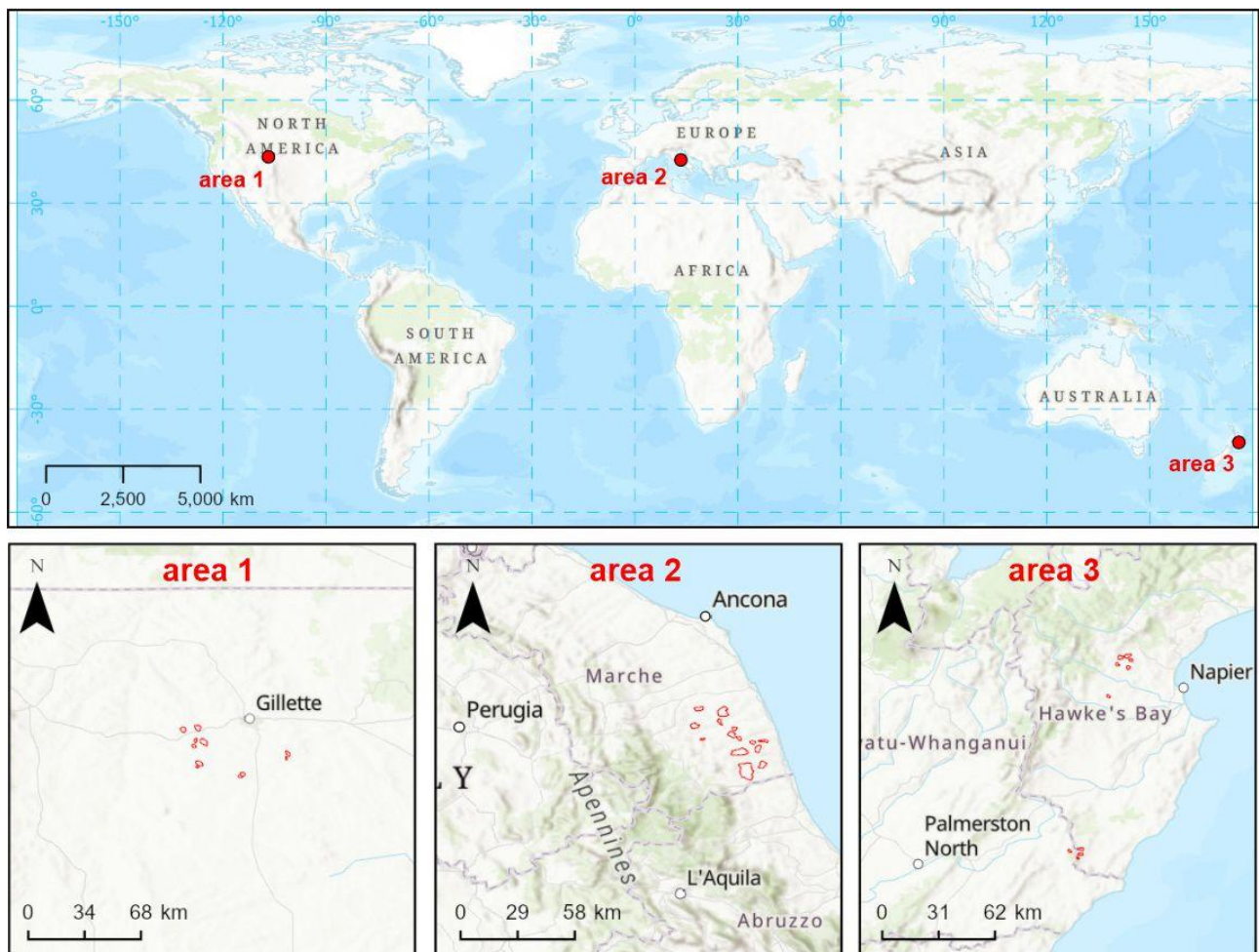


Figure 1. Location map of the study areas with indication of the catchments analyzed (red polygons).

Due to its elevation, this part of Wyoming experiences a relatively cool, arid climate, with average annual maximum temperatures around 15 °C and minimum temperatures close to 1 °C. The presence of mountain ridges that intercept humid air masses from the Pacific Ocean contributes to the generally low precipitation, averaging from 400 to 450 mm per year (US Climate Data, usclimatedata.com). In this sector, gully erosion processes are particularly effective due to the poor soil cover and the near absence of tall vegetation (Figure 2b).

2.1.2. Area 2—Central Italy

This area covers a sector of about 1200 km² on the Adriatic side of central Italy (Figure 3a). It is characterized by a predominantly high-hilly and hilly landscape with altitudes (generally below 500–600 m a.s.l.) that decrease progressively eastward to the coastal belt. The slopes are mainly used for agriculture, while small urban settlements and inhabited centers are mainly located along the watersheds. The essentially homogeneous bedrock is characterized by Plio–Pleistocene formations consisting of alternating shale and sandy-conglomeratic layers [31,32]; these formations are locally covered by medium-fine continental deposits (colluvial and/or fluvial). The structural framework of the Plio–Pleistocene formations is expressed at the surface as a regular, eastward-dipping monocline, formed as a result of the regional tectonic uplift that began in the Early Pleistocene [33]. Overall,

the monoclinical structure is offset by a few dip-slip faults, mainly oriented to NNW–SSE and WSW–ENE, with displacements rarely exceeding 10 m [32]. These tectonic features, however, do not produce significant surface morphological evidence, nor do they exert a notable influence on the hydrographic network.

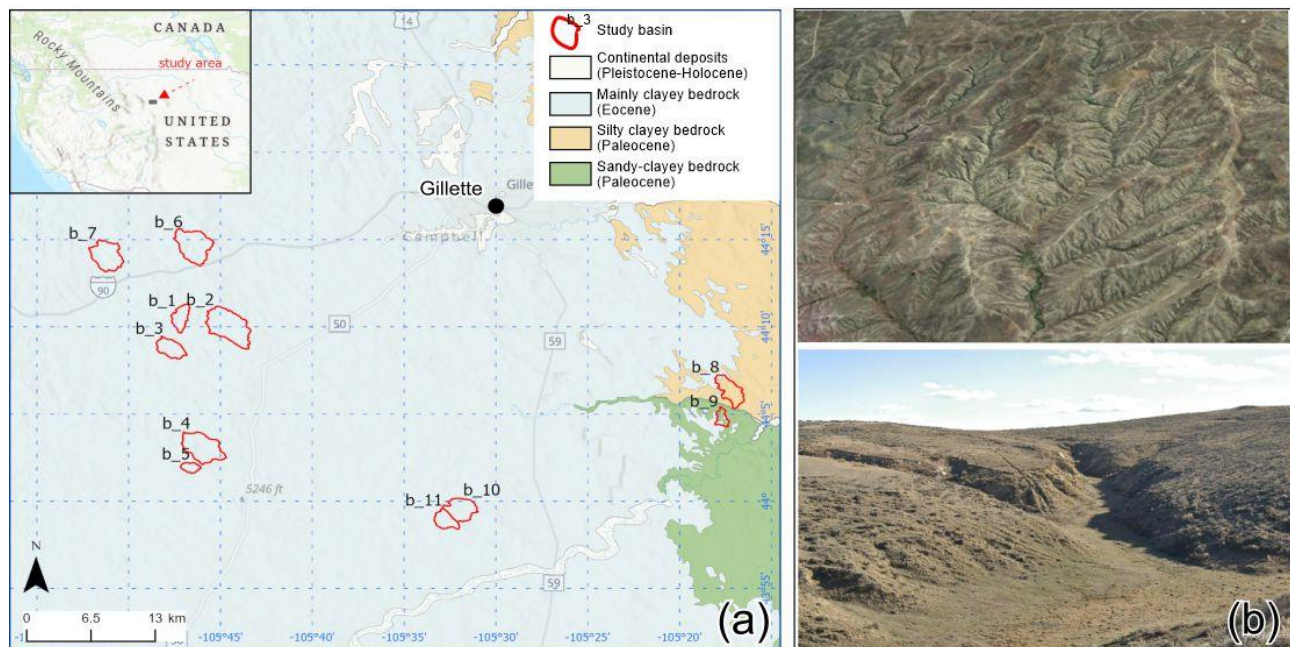


Figure 2. (a) Lithological sketch of Area 1 with the location of the basins investigated; (b) typical gullies visible from satellite image (top, source © Google Earth, 2025) and the ground (bottom). Modified from [28].

From a climatic perspective, the area represents a transition zone between the Mediterranean climate, typical of southern Italy, and the humid subtropical (or temperate oceanic) climate, which is widespread across much of the territory [34,35]. The study area records an average annual temperature of about 14 °C, with maximums in July and August and minimums in January. Precipitation ranges from around 600 mm along the coast to 1000 mm in the higher hilly sector. The relationship between temperature and rainfall indicates a slight summer aridity in the low-hilly and coastal zones from July to mid-September. Under these conditions, gully erosion processes are fairly common [36,37], although dense perfluvial vegetation (Figure 3b) sometimes obscures their activity. On the other hand, this vegetation makes the transition between gully-affected areas and the slope areas dominated by widespread rill erosion more clearly visible.

2.1.3. Area 3—New Zealand

The third study area covers two sectors, totaling approximately 400 km² on the eastern side of the North Island, New Zealand (Figure 4a,b). The landscape, in general, is characterized by a typical high-hilly terrain with altitudes between 200 and 600 m a.s.l., which progressively decrease towards the east and the coastal belt. In the northernmost sector, land use is dominated by intensive horticulture and viticulture, supported by the region's highly productive soils and favorable climate, alongside significant areas of pastoral farming, forestry, and increasingly, urban development. In the southernmost sector, the territory is mainly exploited for livestock grazing, primarily sheep and bulls. However, in several areas, the slopes are entirely uncultivated or covered in forests (data from Operative Hastings District Plan at <https://eplan.hdc.govt.nz/eplan> (accessed on 22 June 2026)).

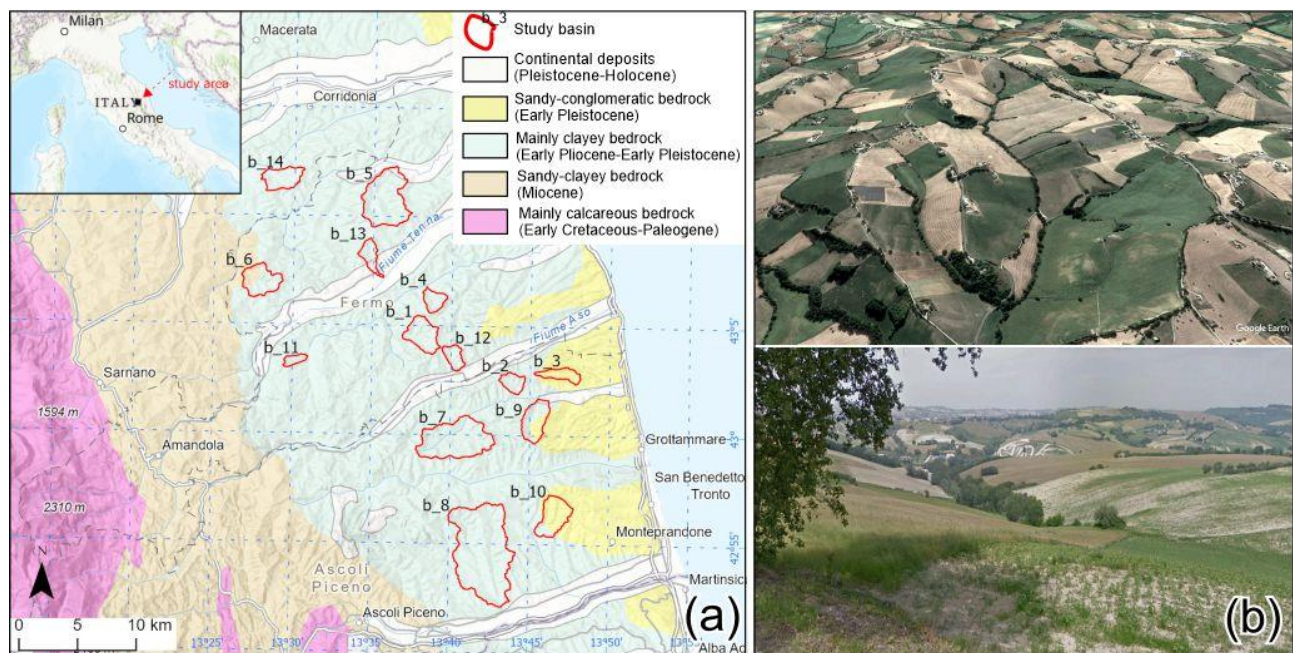


Figure 3. (a) Lithological sketch of Area 2 with the location of the basins investigated; (b) typical gullies visible from satellite image (top, source © Google Earth, 2025) and the ground (bottom). (Modified from [28]).

The whole area occupies a now-uplifted part of a late Neogene forearc basin and associated inboard margin of an accretionary wedge, which are all part of the actively deforming Hikurangi subduction margin, inferred to have commenced between 40 and 24 Ma [38,39]. From a lithologic point of view, the bedrock in the northernmost sector is mainly characterized by the presence of alternating mudstones, sandstones, and conglomerates belonging to the Mangaheia Group, a shallow-marine, limestone-bearing Pliocene succession up to 1.5 km thick; the southernmost sector, on the other hand, is characterized by the presence of prevalent mudstones and sandstones of different ages (Cretaceous to Miocene). Despite the complex geological setting, its influence on the hydrographic network and, in general, on surface geomorphological processes appears rather limited [40]. Although the New Zealand test area is located, as stated above, within the broader Hikurangi subduction-margin system, the selected basins were chosen to minimize direct structural control on drainage development. This was checked by overlaying the basin boundaries and extracted drainage network on the GNS Science 1:250,000 Geological Map of New Zealand and on the New Zealand Active Faults Database. The analyzed basins show mainly dendritic to sub-dendritic drainage patterns, with no systematic alignment of first- to third-order channels along significant, mapped active-fault traces and no clear fault-parallel control of basin divides or main channels. Therefore, tectonic activity is acknowledged as part of the regional geological setting, but it is not considered a dominant local control on the morphometric parameters used in this study.

Sheltered by mountain ranges to the west, this area benefits from a predominantly dry and sunny climate. Summer is usually characterized by warm, stable, and dry weather; during winter, frost may occasionally occur. Typical daytime maximum temperatures in summer range between 20 °C and 28 °C, with occasional peaks above 30 °C. High heat is a common feature of the season and can be intensified by strong, dry föhn winds blowing from the northwest. Extreme values up to 39 °C have been recorded. In winter, conditions are milder in the northern part of the region and cooler in the southern areas, with usual daytime highs between 10 °C and 16 °C. Heavy rainfall can develop under easterly or southeasterly flows (data from the National Institute of Water and Atmospheric Research-

NZ at <https://niwa.co.nz/> (accessed on 22 June 2026)). Under such conditions, gully erosion is widespread (Figure 4c), affecting about 10% of the land area [41].

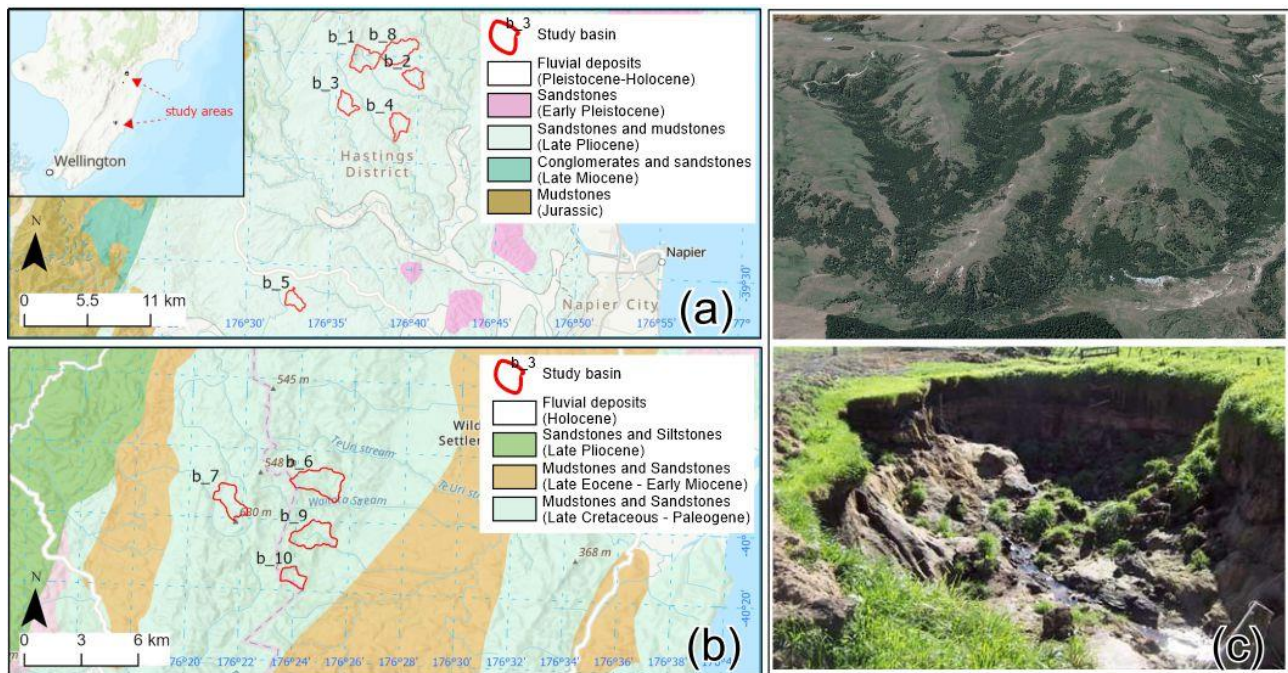


Figure 4. Lithological sketch of Area 3—(a) northern sector, (b) southern sector—with the location of the basins investigated; (c) typical gullies visible from satellite image (top, source © Google Earth, 2025) and the ground (bottom).

3. Methodology

The study has been organized in several steps:

- Calculation of the basic morphometric parameters of all the subbasins.
- Construction of the hypsometric curve.
- Analytical determination of the energy potential of running waters within the individual subbasin.
- Calculation of Şen's "energy index" (Şen, 2019) [42] for gully-head formation.
- Detection of gully heads within the sample basins through satellite image interpretation.

3.1. Calculation of the Basic Morphometric Parameters of All the Subbasins

Basic morphometric parameters have been calculated using ArcGIS Pro software (ESRI, v.3.5.3) and DTMs with a 10 m resolution; the latter can be downloaded free of charge from the links <https://doi.org/10.13127/tinitaly/1>, <https://portal.opentopography.org/>, and <https://maps.gns.cri.nz/> (accessed on 22 June 2026) for the Italian, US, and New Zealand catchments, respectively. Selecting a DTM with an appropriate resolution is crucial. Today, global datasets of relatively high resolution (10–30 m) are accessible, while local or regional sources, such as LiDAR, can provide even finer detail. Our primary objective was to not only use the highest-resolution DTMs available, but also to design a processing approach adaptable to a wide range of DTMs, which represents an excellent option for morphometric analysis [28,43,44]. In this study, we deliberately did not use 1 m resolution LiDAR data, as they can generate "false" elevation variations in semi-urbanized areas, often caused by features such as roads or pathways [28]. These anomalies may introduce inaccuracies in GIS-based determination of "flow direction".

It is important to note that the DTMs are not perfectly equivalent in terms of vertical accuracy and origin (i.e., for TINITALY, the overall RMSE is less than 3.5 m, while for USGS, it is 0.82 m). To minimize inconsistencies, the same preprocessing workflow was applied to all areas: the elevation datasets were projected to a metric coordinate system, clipped to the basin boundaries, checked for artifacts, hydrologically corrected using the Fill tool, and then used to derive slope, flow direction, flow accumulation, stream order, hypsometric curves, and Energy Index rasters. As the proposed method is based mainly on relative elevation, normalized basin area, and elevation belts rather than on absolute erosion volumes, small differences in vertical accuracy are not expected to affect the first-order interpretation. After acquiring the DTMs and refining them by clipping along the basin boundaries, we removed all sinks using the “Fill tool” (Spatial Analyst) to obtain “hydrologically” correct DTMs. We then calculated a series of basic morphometric parameters, including area, perimeter, mean slope, maximum and minimum elevation, and the “Circularity ratio”, defined as the ratio between the basin area and that of a circle with the same perimeter [45]. The drainage network was classified using the [46] method, which assigns orders to streams based on their hierarchy. From the reconditioned DTM, flow direction and flow accumulation rasters were generated in GIS, with a 10-cell threshold applied to define the stream network. Finally, the ArcGIS “Stream Order” and “Stream to Feature” tools were used to produce stream order rasters and polyline features representing river reaches by order.

After defining the hydrographic network, we produced a flow contribution curve (FCC, Ciccolini et al., 2024 [28]) for each stream order, showing the number of river segments distributed across different elevations. This value, denoted as Nuz , corresponds to the number of stream sections intercepted at a given elevation z (Figure 5a). It was obtained by counting the intersections between the hydrographic network vector file and the contour lines extracted from the DTM (Figure 5b), with a contour interval set at 10 m for consistency with previously derived parameters. Therefore, we represented the number of reaches by order (Nuz_I for first-order streams, Nuz_II for second-order, etc.), which allowed us to analyze the distribution and quantity of reaches at different elevations. To make this representation comparable with other parameters described later, we generated semi-dimensional curves with normalized basin area values (a/A between 0 and 1, Figure 5c). This graphical representation highlights elevation ranges corresponding to peak values, which indicate where fluvial erosion was particularly effective. Finally, we calculated the mean of the contribution areas upstream of the third-order streams obtained previously. As explained in detail below, this can be considered the area required to activate significant erosive processes.

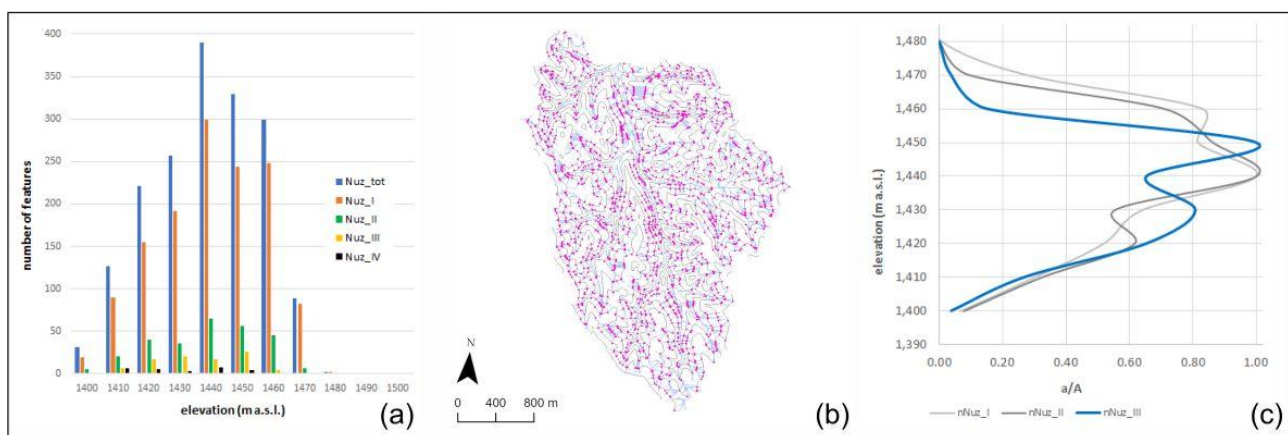


Figure 5. (a) Frequency distribution histogram showing the number of reaches (Nuz_i) divided per order; (b) example of basin with the points of intersection (in purple) between the vector file of the

hydrographic network and the vector file of the contour lines extracted from the DTM; (c) example of flow contribution curve (FCC) relating to the first three orders of hydrographic network.

3.2. Construction of the Hypsometric Curve

To estimate the mean elevation of each basin and compare the previously obtained FCC trends, we constructed hypsometric curves [18], using the ArcGIS “CalHypso” tool [47]. These curves represent the proportion of basin area above a given elevation. Typically expressed in non-dimensional form (relative height h/H vs. relative area a/A), these curves allow comparison among different basins. For this study, to better highlight correlations between other relative elevations, we also created semi-dimensional curves with normalized basin area values (Figure 6). The hypsometric curve, modeled with a 3rd-degree polynomial, identifies two oblique inflection points (OIPs): one within the basin, where slope energy shifts from rapid to slower mass loss [18], and another outside the diagram, which is only a mathematical solution with no physical meaning, as it lies below the basin outlet. These special points are therefore calculated for each subbasin. A third-degree polynomial was adopted because it is the lowest-order function capable of representing an internal inflection point of the hypsometric curve, which is required for identifying the oblique inflection point. The same polynomial degree was used for all basins to maintain methodological consistency. Goodness-of-fit was evaluated for each basin using the coefficient of determination, with resulting R^2 values ranging between 0.97 and 0.99.

3.3. Analytical Determination of the Energy Potential of Running Waters Within the Individual Subbasin

The hypsometric curve can also be used to define the energy potential of each point within a drainage basin. Starting from simple physical–mathematical relationships, it is known that if a water particle of mass m moves without friction and descends by a value dh , by the principle of conservation of potential and kinetic energy, we have:

$$mgh + \frac{1}{2}mv^2 = mg(h - dh) + \frac{1}{2}m(v + dv)^2 \quad (1)$$

where v is the velocity (L/T) and g is the gravitational acceleration (L/T²).

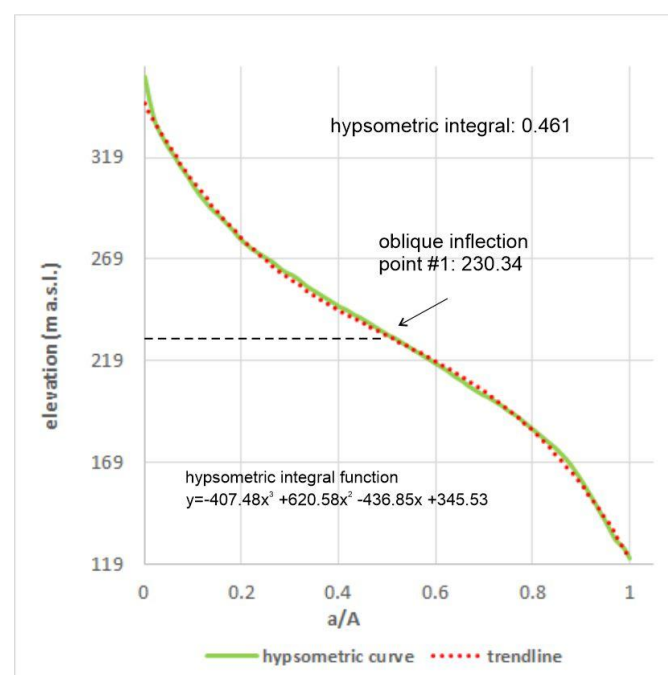


Figure 6. Example of hypsometric curve with indication of value and location of the relating oblique inflection points (OIPs).

Simplifying for m , once the square of the binomial has been developed at the second term, and taking into account that the quantity dv^2 is very small and can be neglected, we obtain:

$$gdh = vdv \quad (2)$$

Integrating the two terms of the equation, respectively, in dh and in dv , we have:

$$v = \sqrt{2gh} \quad (3)$$

Finally, substituting v in the formula for the power ($P = Fv = mgv \sin \alpha$), where F is the force, we have:

$$P = (mg \sin \alpha) \sqrt{2gh} \quad (4)$$

This formula tells us that in the hypsometric curve for $h = 0$, the power $P = 0$ and that for $h = 1$, $P = (mg \sin \alpha) \sqrt{2g}$ with P expressed in Watts. Evidently, this is an “ideal” system that does not account for energy dissipated by friction, but in absolute terms, it can be compared with the morphometric evaluations.

To apply the method to each basin in GIS, we used the following procedure. Starting from the DTM (10 m resolution, Figure 7a), a raster of the h/H values of the hypsometric integral, divided into 20 classes between 0 and 1 (Figure 7b), and a raster of the slope in radians (Figure 7c) were created. Applying the formula, a raster of the power p values per unit mass m is obtained (Figure 7d).

3.4. Calculation of Şen's “Energy Index” for Gully Head Formation

The value of the power P , although significant, cannot be directly related to the relationship between height and relative area (as in a hypsometric curve) and energy in a drainage basin.

One possible solution is to use a method commonly used to measure the electric potential in a drainage basin (for example, in the presence of a dam). The “single-point” method, which relates hydroelectric energy P , specific density of water γ , flow rate Q , and head H , is the most widely used alternative [42]. Şen's Energy Index, to our knowledge, has not previously been applied directly to gully-initiation prediction. Its use in this study is therefore an original geomorphological adaptation. The adaptation is justified because the index combines normalized elevation and contributing area, which are key topographic controls on runoff concentration and potential erosive work. The index will consequently be interpreted as a relative morphometric indicator of erosion potential, and its validity will be assessed empirically by comparison with mapped gully-head elevations.

$$P = \gamma * Q * H \quad (5)$$

This approach does not account for the drainage basin's elevation difference, but relies solely on the water height at a single point along the main drainage channel. Theoretically, the differences in power gain dP , elevation dH , and flow rate dQ can be obtained from Equation 6:

$$dP = \gamma * dQ * dH \quad (6)$$

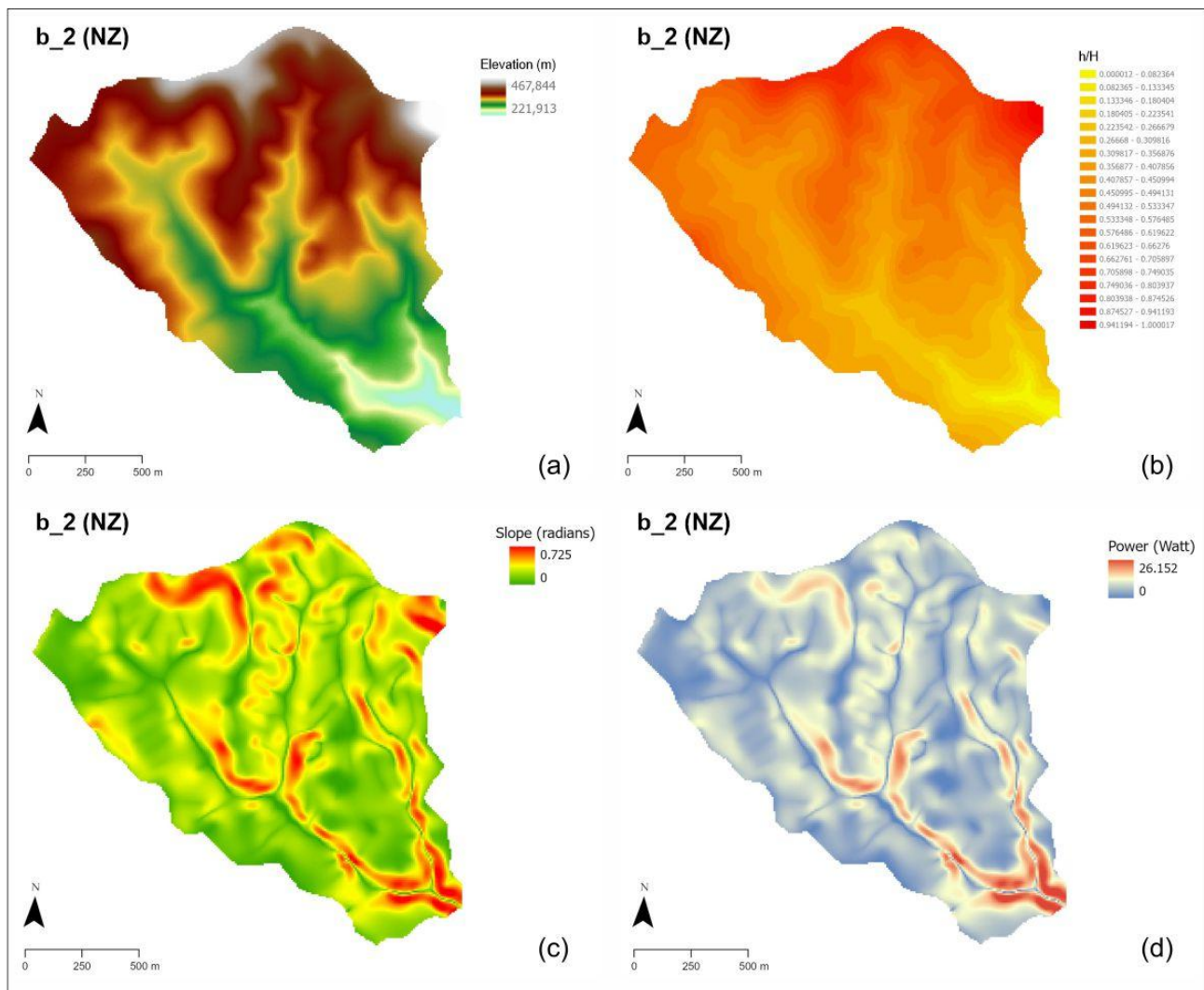


Figure 7. Procedure for calculating the energy potential of running waters: (a) DTM with 10 m resolution; (b) h/H raster; (c) basin slope in radians; (d) power p of the basin expressed in Watts.

One way to relate discharge to basin area and the “energy” of the water, such as rainfall intensity, is to use a formula like the Rational Method [48], a simple but widely used hydrological technique for estimating peak discharge from small drainage basins. It relates rainfall intensity (I), catchment area (A), and a runoff coefficient (C) to calculate the maximum flow rate (Q).

$$Q = C * I * A \quad (7)$$

Substituting these terms into Equation (6), we obtain:

$$dP = \gamma C I * dA * dH \quad (8)$$

If we assume the density of water is 1, the runoff coefficient is 1 (considering only the drainage area and altitude, without geological influences), and the rainfall intensity is also 1 (i.e., the drainage basin, effective over the entire area, can be adjusted according to rainfall intensity), we can write

$$dP = dA * dH \quad (9)$$

The product of the infinitesimal increase in drainage area and the decrease in elevation is defined as the Energy Index (Ei) of the drainage basin [49], where hydrometeorological and geological effects are not considered. In practice, Ei can be defined as the in-

finitesimal energy per unit density of a basin subjected to constant rainfall intensity and a unit runoff coefficient.

The Energy Index can therefore be easily adapted to the hypsographic curve of a basin by normalizing the heights and the relative contributing areas to 1.

$$Ei = h/H * a/A \quad (10)$$

This approximation allows us to consider the energy associated with the action of surface running water within a hydrographic basin in absolute terms and, consequently, to compare basins of very different sizes and morphometric characteristics.

It is important to point out that the calculated energy should not be interpreted as the actual physical energy of runoff in the field. The model is intentionally simplified and does not include friction losses, infiltration, soil resistance, vegetation roughness, sediment transport, or spatially variable runoff. It therefore provides a relative morphometric energy indicator, based on normalized elevation and contributing area, which is useful for identifying potential zones of concentrated incision but does not replace process-based hydrological or hydraulic modeling.

3.5. Detection of Gully Heads Within the Sample Basins Through Satellite Image Interpretation

The correspondence between the results of the analytical procedures described above and the presence of erosive processes linked to gullies was verified using high-resolution satellite images from Google Earth (© Google, 2025); data sources include Landsat/Copernicus and Maxar Technologies (Figure 8).

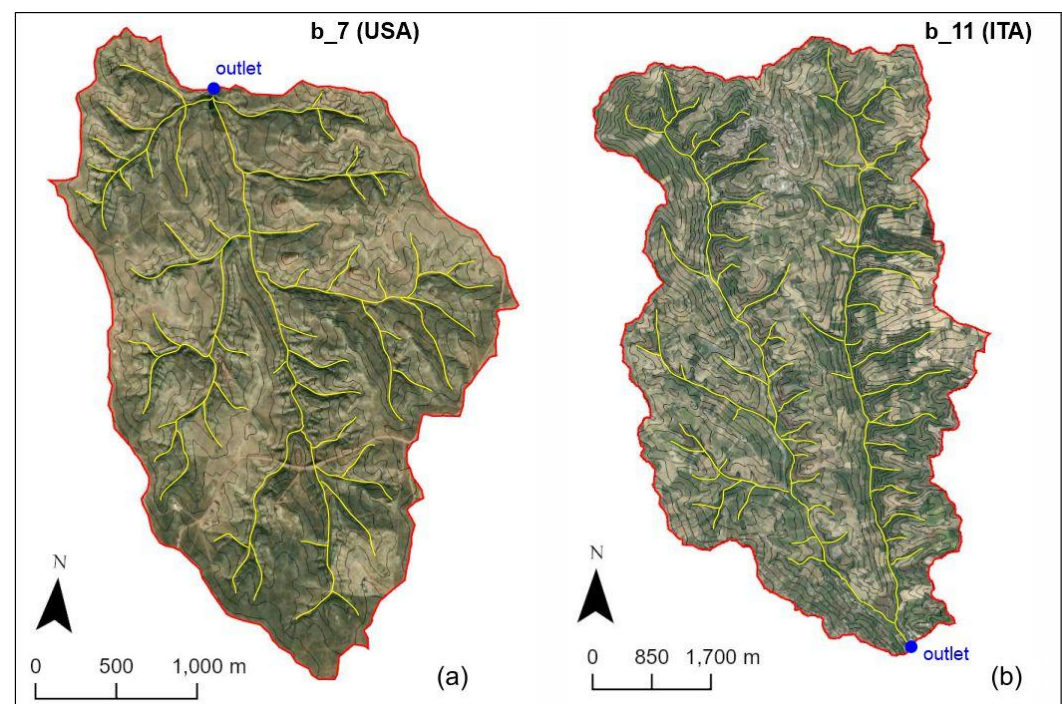


Figure 8. Mapping of gullies (yellow lines) through the analysis of satellite images (source © Google Earth, 2025). (a,b) A 20% trimmed mean of the relative elevations was obtained in order to exclude anomalous values linked to possible (although minimal as mentioned in the introduction to this study) influences of anthropogenic and/or geological–structural origin on the development of these processes. As already mentioned, the value obtained represents a statistically representative elevation belt, rather than a unique physical elevation threshold.

4. Results

The results of the steps a, b, and e described above are summarized briefly in Table 1 and in complete form in Annex 1. By comparing some parameters obtained from the analysis, it is possible to identify relatively narrow sectors within each catchment that can be directly linked to erosive processes associated with surface running waters. The graphs in Figure 9 for nine sample catchments (three from each study area) show, in semi-dimensional form, the FCCs for the first three order reaches and the corresponding hypsometric curve. The FCCs all display a general bell-shaped distribution with respect to elevation, indicating that the greatest number of network segments develop in relatively limited sectors of the catchment. The highest-order reaches (second- and third-order) also exhibit more pronounced peaks corresponding to specific heights within the catchment. Once the hypsometric curve was plotted, it was possible to determine two further heights: the mean basin height (H_{mean} in Table 1, dashed light green line in the graph) and the corresponding OIP (oblique inflection point). As shown in the graphs, these two elevations and the one corresponding to the most pronounced peak of the FCCs (generally that of the third-order reaches—dashed red line, $H_{mean_III\ FCC}$ in Table 1) have very similar values, almost coinciding in some cases; this specific stream order, as mentioned above, is purely indicative since it is known to depend on the scale of representation. Even the standard deviation σ calculated for the “heights” of each basin is consistently below or around 10 m (the acceptable error for the resolution of the chosen DTM); only five of the selected basins show a standard deviation between 15 and 20 m. The dashed black line, on the other hand, indicates the mean height of the gullies identified through satellite imagery analysis ($H_{mean_gullies\ field}$ in Table 1). In most of the analyzed basins, this elevation is very close to those previously described, while in some it differs by even a few dozen meters, as in Basin 1 within Area 1 (USA) or Basins 3 and 8 in Area 2 (Italy).

Table 1. Summary table with all the processing results described in the text.

BASIN	Area (km ²)	Average Slope	Circularity Ratio	Hypsographic Curve Function	Hypsometric Integral	OIP (m)	Hmean_gullies Field (m)	Hmean (m)	Amean_III Contr (m ²)	Std. Dev.	σ
Basin 1 ITA	6.18	0.30	0.372	$y = -474.13x^3 + 696.78x^2 - 435.58x + 332.08$	0.431	230.16	230.50	227.35	13,406.00	9.03	
Basin 2 ITA	2.65	0.30	0.445	$y = -252.79x^3 + 396.49x^2 - 345.44x + 289.78$	0.473	181.40	196.50	184.90	15,008.00	5.68	
Basin 3 ITA	2.91	0.29	0.271	$y = -236.06x^3 + 378.18x^2 - 436.5x + 353.27$	0.483	192.07	195.91	202.04	10,656.00	12.09	
Basin 4 ITA	2.68	0.28	0.394	$y = -290.14x^3 + 441x^2 - 332.68x + 258.58$	0.459	165.45	177.20	166.69	12,666.00	4.57	
Basin 5 ITA	14.63	0.23	0.361	$y = -419.28x^3 + 689.84x^2 - 492.66x + 283.28$	0.401	151.46	169.12	162.08	11,575.00	11.01	
Basin 6 ITA	6.56	0.29	0.387	$y = -277.06x^3 + 371.65x^2 - 328.99x + 397.73$	0.487	300.18	305.15	287.85	13,369.00	21.60	
Basin 7 ITA	16.48	0.27	0.347	$y = -387.87x^3 + 628.63x^2 - 487.95x + 368.95$	0.402	227.69	239.11	236.99	14,587.00	4.73	
Basin 8 ITA	33.83	0.25	0.303	$y = -713.95x^3 + 1207.5x^2 - 793.84x + 372.03$	0.355	180.31	196.15	198.23	11,974.00	19.28	
Basin 9 ITA	6.09	0.34	0.426	$y = -569.25x^3 + 993.29x^2 - 786.07x + 434.41$	0.378	201.14	245.30	229.78	14,443.00	22.05	
Basin 10 ITA	6.88	0.31	0.400	$y = -455.64x^3 + 713.34x^2 - 471.06x + 289.79$	0.417	173.46	185.40	177.92	15,261.00	14.11	
Basin 11 ITA	1.36	0.23	0.364	$y = -292x^3 + 464.27x^2 - 407.38x + 417.52$	0.472	288.55	284.64	295.61	12,201.00	13.74	
Basin 12 ITA	2.61	0.28	0.380	$y = -300.77x^3 + 486.83x^2 - 359.21x + 321.95$	0.439	222.57	193.81	229.48	13,952.00	20.31	
Basin 13 ITA	2.94	0.21	0.247	$y = -407.48x^3 + 620.58x^2 - 436.85x + 345.53$	0.461	230.34	244.94	231.95	15,123.00	5.95	
Basin 14 ITA	5.17	0.21	0.376	$y = -288.65x^3 + 476.31x^2 - 352.24x + 272.39$	0.376	174.71	171.35	182.83	14,883.00	7.25	
Basin 1 USA	2.49	0.14	0.514	$y = -160.06x^3 + 200.51x^2 - 133.42x + 1515$	0.529	1482.57	1485.21	1474.72	12,807.00	6.07	
Basin 2 USA	8.79	0.14	0.574	$y = -166.77x^3 + 235.34x^2 - 165.71x + 1548.2$	0.559	1504.98	1512.44	1502.05	18,468.00	8.08	
Basin 3 USA	3.13	0.14	0.631	$y = -111.84x^3 + 160.36x^2 - 126.23x + 1483.4$	0.481	1447.48	1453.69	1445.21	16,462.00	4.91	
Basin 4 USA	6.88	0.14	0.622	$y = -162.46x^3 + 250.72x^2 - 185.27x + 1566$	0.443	1514.94	1523.71	1516.26	15,345.00	4.91	
Basin 5 USA	1.15	0.14	0.753	$y = -188.45x^3 + 302.21x^2 - 198.28x + 1581.2$	0.465	1532.76	1544.26	1535.71	16,146.00	6.84	
Basin 6 USA	6.86	0.14	0.595	$y = -167.37x^3 + 237.75x^2 - 160.21x + 1494.4$	0.530	1454.10	1449.98	1451.71	16,798.00	1.68	
Basin 7 USA	5.56	0.11	0.630	$y = -122.32x^3 + 160.9x^2 - 111.8x + 1478.4$	0.598	1450.01	1452.55	1445.61	15,529.00	2.50	
Basin 8 USA	3.86	0.15	0.439	$y = -97.791x^3 + 126.93x^2 - 127.11x + 1440.9$	0.472	1401.72	1400.84	1395.11	16,187.00	2.56	
Basin 9 USA	1.27	0.22	0.448	$y = -120.92x^3 + 122.01x^2 - 104.26x + 1453$	0.601	1427.15	1419.11	1411.31	14,992.00	10.02	
Basin 10 USA	4.18	0.07	0.619	$y = -70.996x^3 + 107.49x^2 - 88.141x + 1527.4$	0.506	1501.15	1511.69	1501.36	15,596.00	4.73	
Basin 11 USA	2.46	0.09	0.644	$y = -50.376x^3 + 64.438x^2 - 67.169x + 1523.3$	0.526	1502.48	1504.36	1498.66	16,104.00	2.20	
Basin 1 NZ	3.81	0.19	0.572	$y = -920.45x^3 + 1709.5x^2 - 1084.1x + 629.77$	0.315	395.41	418.77	426.09	19,760.00	13.41	
Basin 2 NZ	2.11	0.22	0.644	$y = -705.4x^3 + 1101.9x^2 - 588.48x + 444.9$	0.442	337.64	340.16	341.92	22,880.00	4.55	
Basin 3 NZ	2.44	0.3	0.524	$y = -752.88x^3 + 980.11x^2 - 455.05x + 400.9$	0.643	326.47	329.12	303.81	17,865.00	9.84	
Basin 4 NZ	1.77	0.09	0.502	$y = -225.46x^3 + 343.42x^2 - 194.62x + 301.34$	0.419	261.54	255.65	259.25	21,667.00	4.36	
Basin 5 NZ	2.92	0.36	0.599	$y = -731.54x^3 + 1090.5x^2 - 675.49x + 509.38$	0.487	353.23	348.29	342.02	18,545.00	4.08	
Basin 6 NZ	1.70	0.3	0.483	$y = -482.88x^3 + 780.08x^2 - 549.21x + 611.06$	0.428	466.11	474.32	469.60	20,974.00	17.57	
Basin 7 NZ	2.38	0.34	0.574	$y = -711.01x^3 + 1084.9x^2 - 628.79x + 457.46$	0.472	324.75	325.15	321.07	15,236.00	2.24	
Basin 8 NZ	0.93	0.39	0.621	$y = -524.44x^3 + 879.23x^2 - 599.38x + 468.01$	0.423	316.10	332.28	328.15	16,669.00	6.41	
Basin 9 NZ	4.58	0.11	0.627	$y = -396.88x^3 + 651.74x^2 - 416.6x + 426.2$	0.465	328.34	331.88	334.28	20,011.00	2.21	
Basin 10 NZ	2.10	0.08	0.550	$y = -260.77x^3 + 410.58x^2 - 227.23x + 337.95$	0.366	294.08	298.39	294.34	14,633.00	2.56	

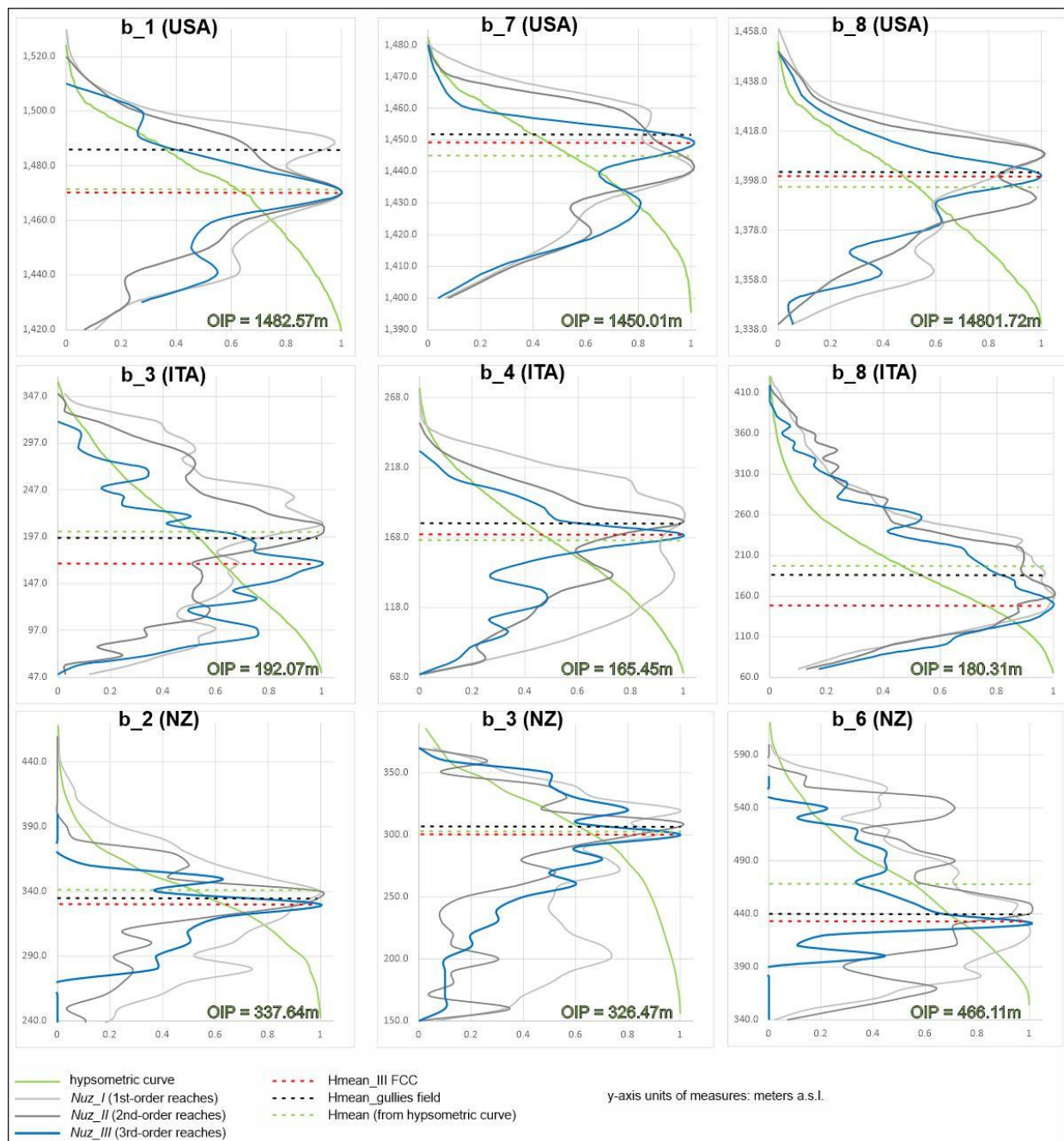


Figure 9. Flow contribution curves (FCCs) of the first three order reaches and the corresponding hypsometric curves related to nine sample basins. Dashed lines of different colors indicate the mean heights of the gullies calculated with different methods; inside each figure, the corresponding oblique inflection point (OIP) is also reported.

This apparent discrepancy, as will be explained in more detail later in the manuscript, may be associated with local “inhomogeneities” of lithological and/or structural or anthropogenic origin within the individual basin.

The data on the mean contribution areas of the III-order reaches (*A_{mean_III contr}* in Table 1) are also very interesting; all these areas fall within a relatively narrow range, with values between 10,000 and 20,000 m² (between 1 and 2 hectares).

The results of the analyses described above enable us to identify, as mentioned, specific sectors within a catchment area where processes related to surface running waters are concentrated. However, these assessments are essentially based on morphometric

analyses or direct observations, without any information on the energy required to activate these processes. The calculation procedure described in point c) of the previous paragraph therefore enables us to identify the sectors of the catchment characterized by the highest values of water potential energy (in terms of power per unit mass). Observing the results (some examples are shown in Figure 10), the correspondence between the maximum energy values and the areas of gully activation within the catchments is very clear. This correspondence was quantified by comparing the mean elevation of mapped gully heads with the basin mean elevation derived from the hypsometric curve. The mean absolute difference is 8.6 m and the RMSE is 10.9 m; 31 of the 35 basins show differences within 15 m. This supports the visual evidence in Figure 10.

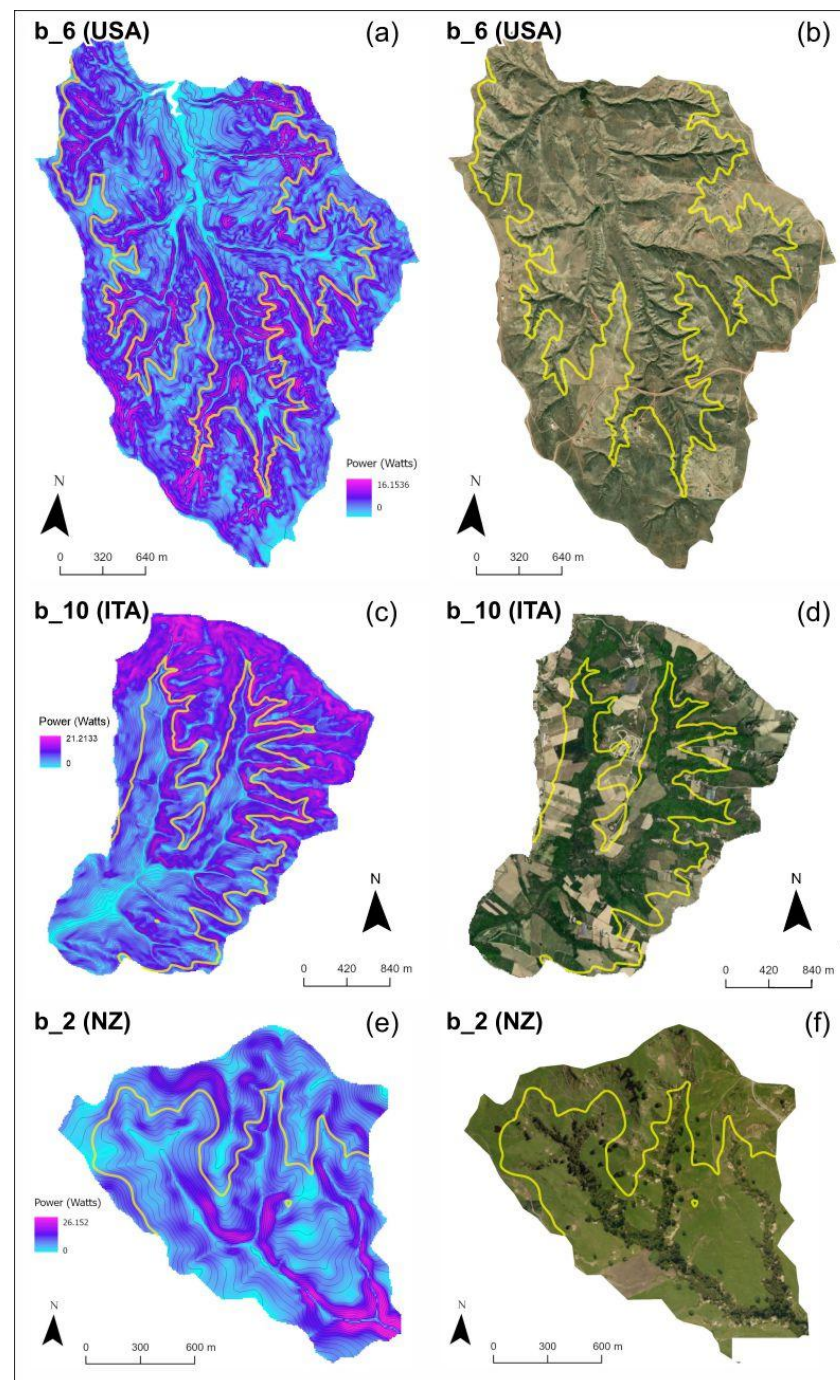


Figure 10. (a,c,e) Rasters of the water potential (expressed in Watts) for three sample basins; (b,d,f) related satellite images (source © Google Earth, 2025); the yellow line indicates the contour line of the mean height of the basin.

Equally significant is the fact that these sectors are generally located at the mean elevation of the catchment area, as calculated from the hypsometric curve. This correspondence therefore allows us to link the energy to the other “elevations” determined with a semi-quantitative procedure from the morphometric analyses. However, the power p value (in Watts), while providing a quantitative indication of the energy of the water at each point in a generic hydrographic basin, is actually a function of parameters such as the mass and slope of the basin and cannot be treated in absolute terms as a function of the hypsometric curve trend.

The Şen’s “Energy Index” E_i , on the other hand, by using normalized (between 0 and 1) areas and elevations, allows for the comparison of basins of very different sizes and morphometric characteristics. Table 2 presents the E_i values for all 35 basins analyzed, along with their respective mean heights.

Table 2. Şen’s “Energy Index” (E_i) calculated for all the basins analyzed.

BASIN	Hmean (m)	Hypsometric Integral	E_i	BASIN	Hmean (m)	Hypsometric Integral	E_i
Basin 1 ITA	227.35	0.431	0.23	Basin 5 USA	1535.71	0.465	0.22
Basin 2 ITA	184.90	0.473	0.23	Basin 6 USA	1451.71	0.530	0.27
Basin 3 ITA	202.04	0.483	0.24	Basin 7 USA	1445.61	0.598	0.31
Basin 4 ITA	166.69	0.459	0.22	Basin 8 USA	1395.11	0.472	0.25
Basin 5 ITA	162.08	0.401	0.19	Basin 9 USA	1411.31	0.601	0.33
Basin 6 ITA	287.85	0.487	0.25	Basin 10 USA	1501.36	0.506	0.24
Basin 7 ITA	236.99	0.402	0.19	Basin 11 USA	1498.66	0.526	0.27
Basin 8 ITA	198.23	0.355	0.16	Basin 1 NZ	426.09	0.315	0.11
Basin 9 ITA	229.78	0.378	0.18	Basin 2 NZ	341.92	0.442	0.22
Basin 10 ITA	177.92	0.417	0.20	Basin 3 NZ	303.81	0.643	0.42
Basin 11 ITA	295.61	0.472	0.23	Basin 4 NZ	259.25	0.419	0.26
Basin 12 ITA	229.48	0.439	0.21	Basin 5 NZ	342.02	0.487	0.27
Basin 13 ITA	231.95	0.461	0.23	Basin 6 NZ	469.60	0.428	0.23
Basin 14 ITA	182.83	0.376	0.17	Basin 7 NZ	321.07	0.472	0.25
Basin 1 USA	1474.72	0.529	0.29	Basin 8 NZ	328.15	0.423	0.22
Basin 2 USA	1502.05	0.559	0.28	Basin 9 NZ	334.28	0.465	0.21
Basin 3 USA	1445.21	0.481	0.24	Basin 10 NZ	294.34	0.366	0.21
Basin 4 USA	1516.26	0.443	0.21				

Examining the results, the average E_i value is 0.24, with a small standard deviation of 0.05. Specifically, the interquartile range (IQR)—the interval between the 25th and 75th percentiles, which indicates the width of the central band of the data—is 0.045; consequently, this band lies between 0.21 and 0.25. The significance of this result is also highlighted from a statistical perspective. The E_i values appear to follow a normal distribution (Figure 11a); however, the Shapiro–Wilk test performed using the rounded values reported in Table 2 does not confirm normality at the 0.05 significance level. Therefore, the distribution is now described more cautiously as approximately bell-shaped and concentrated within a narrow interval. Similar indications are evident in the frequency distribution graph (Figure 11b), which clearly shows that the majority of values are concentrated within a relatively narrow band.

The E_i values obtained fall within the “Low” class as defined by [49], who classifies Energy Index values into five categories, ranging from very low to very high (0 to 1). However, this classification originates from studies evaluating the hydroelectric potential of river basins. As it is necessary to define a minimum energy threshold for activating erosive processes, the E_i values obtained in this study can be considered well justified.

Very interesting information can be obtained by comparing the Energy Index values with other basin morphometric parameters. As shown in the graph in Figure 12a, and confirmed by the Pearson's correlation coefficients, the analysis indicates that the Energy Index is mainly controlled by the hypsometric integral, which shows a strong, statistically significant relationship. The other parameters (Table 3) show weak relationships, with low R^2 values and therefore limited explanatory significance from a geomorphological perspective. (Figure 12b–e).

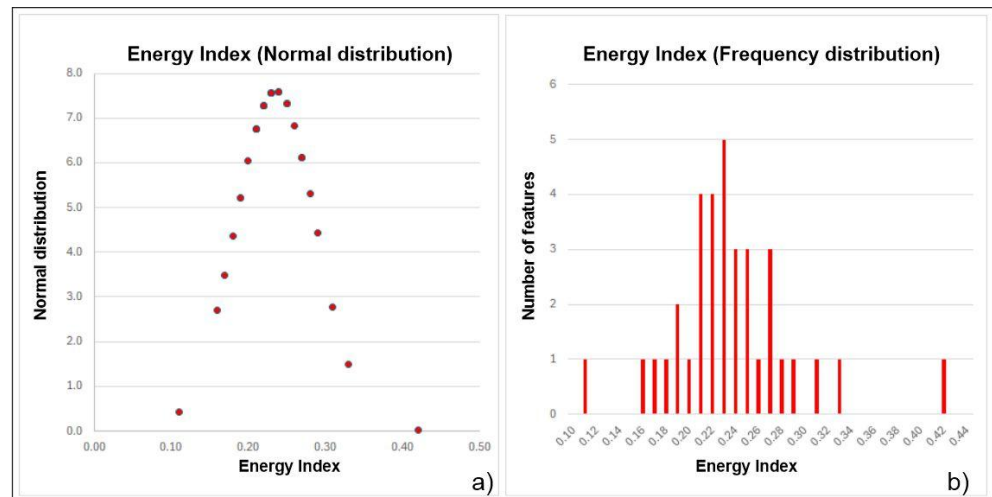


Figure 11. “Bell-shaped” distribution (a) and frequency distribution (b) of the calculated Ei values.

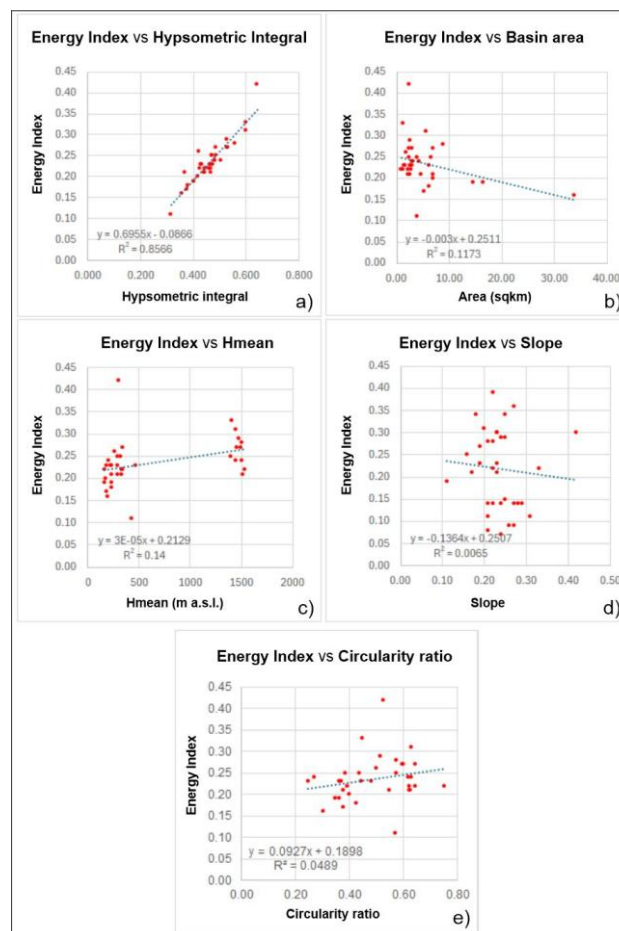


Figure 12. Comparison between Energy Index and some basic morphometric parameters: (a) hypsometric integral; (b) basin area; (c) mean height; (d) average slope; (e) circularity ratio.

Table 3. Pearson’s correlation coefficients between some morphometric parameters and the Energy Index (Ei).

Parameters Correlation	Pearson’s Correlation Coefficients		
	r	R ²	p
Ei vs. hypsometric integral	0.925	0.856	<0.001
Ei vs. basin area	−0.339	0.115	0.046
Ei vs. average slope	−0.08	0.006	0.646
Ei vs. mean height	0.376	0.142	0.026
Ei vs. circularity ratio	0.214	0.046	0.217

5. Discussion

The analyses described in the previous paragraphs provide valuable and original insights for defining, within a generic river basin, the areas most susceptible to triggering “intense” erosion processes (i.e., gully-type erosion).

One of the most notable findings is the strong correlation between heights calculated using different methods (i.e., satellite imagery, GIS, and statistical analyses) and the mean heights derived from hypsometric curves (Table 1). The standard deviation (σ), as noted in the previous paragraph, generally remains below or around 10–15 m, which is an acceptable margin of error given the resolution of the used DTM. Of the five σ values above 15, four are found in Italian basins, which, compared to the other two selected areas, are characterized by a higher degree of anthropization. This fact may be partly related to stronger anthropogenic modification, including agricultural land use, local drainage alterations, road networks, and vegetation cover. This interpretation should be regarded as a plausible explanation rather than a direct causal demonstration, and it is now supported by references documenting the role of land use and human disturbance in gully development [2,37,50]. The proposed method, on the other hand, should be regarded as a first-level topographic screening tool and may not perform equally well in all geomorphic contexts. Its applicability is greatest where concentrated runoff, low-permeability lithology, and basin-scale topographic organization are the dominant controls. Conversely, the method may be less reliable where gully initiation is primarily driven by road drainage, artificial ditches, piping, soil cracking, tillage practices, abrupt land-use change, highly heterogeneous soils, or exceptional rainfall events. In such cases, the morphometric–hypsometric approach should be integrated with field surveys, rainfall data, soil information, and land-use or vegetation mapping.

The inclusion of the “height” corresponding to the activation of third-order reaches among these is considered a secondary aspect, influenced solely by the DTM’s resolution [28]. However, this hierarchical order remains consistent across basins in all test areas and appears unaffected by the main morphometric parameters of the basins (e.g., area, perimeter, shape, slope).

The observed similarities can be explained by the fact that gullies constitute the prevailing morphodynamic mechanism in the highest parts of the basins. Accordingly, the hypsometric curves display the OIPs, where the curve shifts from concave to convex, at essentially the same elevation. These inflection points mark a threshold between low-intensity, areal erosion (sheet and rill), and deep-incision processes (gully formation), and they likely correspond to the elevation at which the greatest decline in potential energy is coupled with the greatest rise in kinetic energy. This concept was already noted by [18], who identified a transition between zones with relatively higher and lower mass-change rates.

Another interesting finding from the study is that the contributing areas upstream of the third-order streams in all basins exhibit comparable characteristics. Calculating the

mean contributing areas for the reaches discussed above (*A_{mean_III} contr*) reveals a consistent pattern: despite belonging to basins that vary widely in size and morphometric traits, these areas cluster within a relatively narrow interval, about 10,000–20,000 m² (1–2 ha; Table 1). Given the distinct rainfall regimes characterizing the three test areas, this similarity is pivotal for interpreting slope-scale erosion mechanisms, as it allows the “position” factor to be treated as the sole effective driver of these processes. Although identifying topographic thresholds for gully-head development is well established in the literature, where threshold conditions are typically expressed as log–log relationships between slope area (A) and slope gradient (S), the procedure adopted here produced valuable values, although they are not always comparable [24,28,51,52]. The slope–area method, on the other hand, is highly effective where detailed gully-head inventories are available, but the threshold coefficients are site-specific and may vary with lithology, soil properties, vegetation, land use, rainfall regime, and DEM resolution. In contrast, the hypsometric/Energy Index approach proposed here operates at the basin scale and aims to identify the relative elevation belt where contributing area, relief distribution, and potential energy favor the onset of concentrated incision. The two approaches are therefore complementary; slope–area thresholds provide local initiation criteria, whereas the present method provides a first-level basin-scale screening of the most likely altitudinal sector for gully initiation. Furthermore, the morphometric/hypsometric method departs substantially from approaches that rely on composite topographic indices to describe catchment hydro-geomorphology, for example, the RUSLE LS factor (sediment transport capacity, [53]), the Stream Power Index (SPI) (potential channel erosion, [54]), the Terrain Characterization Index (TCI) (transport capacity, [55]), and the Topographic Wetness Index (TWI) (topographic control on hydrological processes, [54,56]). Such indices often delineate zones susceptible to various erosion and deposition processes, which do not necessarily coincide with the elevation at which gully heads are initiated.

The most interesting innovation of the study, however, is the ability to quantify in terms of energy the process that leads to the activation of gullies or other intense erosive processes. The Şen’s “Energy Index” *E_i* value, in particular, is consistent with findings from studies evaluating hydroelectric energy potential in river basins. It allows us to determine which sector of the basin, when expressed as a function of its hypsometric curve, exhibits the highest values. These areas are consistently located in the range close to the mean height, confirming that this elevation represents a key point in the geomorphological evolution of the basin. The values obtained (between 0.21 and 0.25), considered in absolute terms, are purely indicative; when compared with the efficiency classes proposed by [49], they would fall into the “low” class (between 0.1 and 0.3), noting that, as repeatedly mentioned, those classes describe the maximum potential for electricity production. In the case of erosional processes, the energy required is certainly lower, and the values obtained can be considered the minimum energy necessary to initiate them. Further confirmation of the utility of the hypsometric curve for identifying the sectors of a basin most susceptible to the initiation of intense erosional processes is provided by the strong correlation between *E_i* and the value of the basin’s hypsometric integral. Indeed, higher values are associated with geomorphologically younger basins and, consequently, with greater “residual” erosive potential. Low correlation was found between *E_i* and basin area, average slope, or mean height, demonstrating that the triggers for these processes are not a function of absolute values but rather of reciprocal values within each basin. The very low correlation between *E_i* and the basin circularity ratio is also not surprising; this parameter, although directly related to a catchment’s predisposition to produce significant discharge peaks during flood events, does not actually express the energy of the water, but rather the characteristic of the hydrographic network to generate flows with a similar concentration time.

6. Conclusions

This study shows that, in low-permeability catchments with limited structural control, mapped gully heads are not randomly distributed along the basin elevation range but cluster around a statistically defined central elevation belt. In particular, it is evidenced that, by relying solely on morphometric analysis and a digital terrain model of suitable resolution, it is possible to estimate the elevation and average contributing area required to trigger accelerated erosion processes in basins that are relatively homogeneous in lithological terms and only weakly, or not at all, influenced by geological–structural factors.

Across the 35 analyzed basins, the mean elevation of mapped gully heads differs from the hypsometric mean elevation by 8.6 m on average, with an RMSE of 10.9 m; 31 basins out of 35 fall within a 15 m difference. This indicates that the hypsometric mean elevation provides a robust first-order descriptor of the elevation belt most prone to gully initiation.

The oblique inflection point of the hypsometric curve, on the other hand, has a clear geomorphic meaning: it marks the transition between the upper basin sector, dominated by diffuse denudation and low-order runoff concentration, and the sector where drainage convergence and relief loss combine to favor deep linear incision. In this sense, the OIP can be interpreted as a morphometric expression of the phase transition from sheet/rill erosion to gully incision.

The contributing areas associated with the initiation belt are also consistently concentrated within a narrow range, mostly around 1–2 ha, while the dimensionless Energy Index is concentrated around a mean value of 0.24, with an interquartile range of 0.21–0.25. These values should not be interpreted as deterministic thresholds, but as central tendency values that define the topographic conditions under which gully initiation is most likely.

Compared with approaches that require a larger set of parameters and/or targeted field surveys, this method is much more flexible and straightforward to apply, especially given the growing availability of powerful IT tools (GIS) and high-resolution digital terrain models.

The practical output of the method is a GIS-based susceptibility belt, combined with Energy Index and drainage-network layers, that can be used to prioritize field checks, erosion-control measures, and land-use planning in basins with comparable lithological and structural conditions.

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Conflicts of Interest: The authors declare no conflicts of interest.

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