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A METHODOLOGICAL FRAMEWORK FOR TERRAIN MORPHOLOGICAL ANALYSIS IN RISK MAPPING BASED ON DEM-DERIVED GEOMORPHOMETRIC PARAMETERS

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Abstract

This study proposes an integrated methodological framework for terrain morphological analysis based on high-resolution digital elevation models (DEMs) and a comprehensive suite of geomorphometric parameters, including slope gradient, slope aspect, profile and plan curvature, relative relief, hypsometric indices, flow accumulation, topographic wetness index (TWI), and terrain roughness. These parameters are quantitatively derived using standardized GIS-based algorithms and systematically analysed to capture terrain heterogeneity, hydrological controls, and structural influences on surface and subsurface processes. The morphometric variables are integrated within a geospatial analytical environment through multi-criteria spatial modelling techniques, enabling the structured assessment of terrain susceptibility and the delineation of areas potentially prone to geomorphological instability. The proposed framework emphasizes methodological consistency, reproducibility, and adaptability across different environmental contexts. By formalizing the relationships between terrain attributes and geomorphological processes, the approach provides a scientifically grounded basis for supporting hazard assessment and risk mapping applications. The framework is intended to contribute to evidence-based decision-making in land-use planning, environmental management, and disaster risk reduction, facilitating the development of consistent and operational risk mapping methodologies.

Key words*: digital elevation models (DEMs), geomorphological hazard assessment, geomorphometric parameters, multi-criteria spatial modelling, terrain morphological analysis.*

INTRODUCTION

Terrain morphology exerts a direct control on geomorphological processes by influencing runoff generation, sediment transport, infiltration dynamics, and slope instability, thereby shaping spatial patterns of hazard susceptibility. The increasing availability of high-resolution digital elevation models (DEMs) has enabled the transition toward quantitative terrain analysis based on reproducible geomorphometric parameters (Moore et al., 1991; Wilson & Gallant, 2000).

Geomorphometry provides the methodological basis for deriving terrain attributes directly linked to hydrological and geomorphological processes (Pike et al., 2009). Key parameters include slope gradient, aspect, curvature, and terrain roughness, which describe slope dynamics and erosion susceptibility, as well as flow accumulation and the topographic wetness index (TWI), which quantify runoff concentration and moisture distribution (Beven & Kirkby, 1979; Tarboton, 1997). In addition, hypsometric indices and relative relief provide quantitative measures of landscape structure and evolution (Strahler, 1952; Pike & Wilson, 1971).

Within Geographic Information Systems (GIS), these variables can be systematically derived, standardized, and integrated, enabling multi-criteria spatial modelling of hazard susceptibility. Such approaches allow the combination of multiple terrain parameters into structured analytical models that capture the interactions between topography and geomorphological processes (Burrough & McDonnell, 1998; Guzzetti et al., 1999; Reichenbach et al., 2018).

Despite these developments, a major limitation remains the lack of standardized frameworks for the selection, computation, and integration of geomorphometric parameters. Existing studies often rely on heterogeneous datasets, variable spatial resolutions, and inconsistent weighting schemes, which reduce reproducibility and comparability (Hengl & Reuter, 2009; Evans, 2012). Moreover, the increasing complexity of spatial modelling techniques has not always been accompanied by transparent methodological structuring.

This study addresses these limitations by proposing an integrated and reproducible methodological framework for terrain morphological analysis based on DEM-derived geomorphometric parameters. The approach focuses on the systematic derivation, standardization, and integration of terrain variables within a GIS-based multi-criteria analytical environment, with direct applicability to risk mapping.

By formalizing the relationships between terrain attributes and geomorphological processes and structuring the computational workflow, the proposed framework enhances methodological consistency and supports the development of transferable and operational approaches for hazard assessment and risk mapping.

Geomorphometric Framework for Terrain Analysis

Geomorphometry provides a quantitative framework for terrain characterization through the derivation of morphometric parameters from digital elevation models (DEMs). These parameters describe the geometry, hydrological behavior, and structural complexity of the land surface and are widely used as proxies for geomorphological susceptibility in risk mapping (Pike et al., 2009; Hengl & Reuter, 2009).

Terrain morphology controls runoff concentration, infiltration, erosion, sediment transport, and slope instability, as these processes are directly influenced by local gradients, curvature conditions, and the spatial arrangement of topographic surfaces (Moore et al., 1991; Wilson & Gallant, 2000). Consequently, the quantitative extraction of terrain attributes enables the formalization of relationships between land-surface configuration and process dynamics.

Among the primary geomorphometric variables, **slope gradient** expresses the maximum rate of elevation change and constitutes one of the most important controls on gravitational processes and runoff velocity. It is calculated as:

$$S = \arctan\left(sqrt\left(\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2\right)\right)$$

where z represents elevation and ∂z/∂x, ∂z/∂y are the first derivatives of the surface. High slope values generally indicate increased susceptibility to erosion and mass movement (Moore et al., 1991).

Slope gradient directly influences the balance between driving and resisting forces acting on surface materials. Steep slopes are associated with increased shear stress, favouring mass movement processes such as shallow landslides, debris flows, and rockfalls, whereas low-gradient surfaces promote sediment accumulation and characterize depositional environments (Moore et al., 1991; Wilson & Gallant, 2000).

From a hydrological perspective, slope gradient controls runoff velocity, infiltration capacity, and flow concentration. High values enhance surface runoff and erosion, while gentle slopes favour water retention and may contribute to saturation under specific conditions (Beven & Kirkby, 1979; Tarboton, 1997).

Within risk mapping, slope gradient represents a primary conditioning factor, widely used in multi-criteria spatial models where higher values correspond to increased susceptibility. Its spatial distribution enables the identification of threshold zones with significant changes in process dynamics and enhances predictive capacity when integrated with other geomorphometric parameters such as curvature and flow accumulation (Guzzetti et al., 1999; Reichenbach et al., 2018). Derived consistently from DEMs, it ensures reproducibility and supports standardized risk assessment methodologies.

Slope aspect defines the orientation of the slope and influences solar radiation, evapotranspiration, soil moisture, and vegetation distribution. It is commonly expressed as:

$$A = \arctan\left(\frac{\frac{\partial z}{\partial y}}{-\frac{\partial z}{\partial x}}\right)$$

Aspect acts as an indirect control on weathering intensity and hydrological response (Wilson & Gallant, 2000).

South-facing slopes (in the Northern Hemisphere) typically experience higher solar radiation, leading to increased evapotranspiration, reduced soil moisture, and enhanced weathering rates, whereas north-facing slopes tend to retain moisture and favour vegetation development.

Within risk mapping, aspect contributes to the differentiation of terrain units with contrasting hydrological and geomorphological behaviour. It is particularly relevant in identifying zones prone to desiccation, soil degradation, or, conversely, moisture accumulation and instability. When integrated with slope gradient and other morphometric parameters, aspect enhances the spatial discrimination of susceptibility patterns, especially in relation to landslides, erosion processes, and vegetation-controlled stability (Moore et al., 1991; Wilson & Gallant, 2000).

Second-order derivatives are represented by **profile curvature** and **plan curvature**, which describe the curvature of the terrain surface in the downslope and contour directions, respectively. These parameters are derived from second partial derivatives of elevation and indicate zones of flow acceleration, deceleration, convergence, and divergence (Evans, 2012). In simplified form, curvature is related to:

$$\left(\frac{\partial^2 z}{\partial x^2}\right), \left(\frac{\partial^2 z}{\partial y^2}\right), \left(\frac{\partial^2 z}{\partial x \partial y}\right)$$

Convex surfaces are generally associated with runoff dispersion and erosional dominance, while concave areas promote flow concentration and material accumulation.

Within geomorphological analysis, profile curvature controls the acceleration or deceleration of flow along the slope, directly influencing erosion and deposition rates, while plan curvature governs lateral flow convergence and divergence, affecting runoff concentration and channel initiation.

In risk mapping, curvature parameters are essential for identifying zones of instability, as areas of flow convergence and concavity are more prone to water accumulation, increased pore pressure, and slope failure. When combined with slope gradient and flow-related indices, curvature significantly enhances the spatial prediction of landslide susceptibility and erosion-prone areas (Moore et al., 1991; Wilson & Gallant, 2000).

Relative relief measures the elevation range within a spatial unit and is defined as:

$$R_r = Z_{max} - Z_{min}$$

This parameter reflects local topographic energy and terrain dissection, with high values indicating stronger geomorphic activity and instability potential (Strahler, 1952).

A complementary indicator is the **hypsometric integral (HI)**, which describes the distribution of elevation within a terrain unit:

$$HI = (\bar{Z} - Z_min)/(Z_max - Z_min)$$

where $\bar{Z}$ is the mean elevation. Hypsometric analysis provides information on the evolutionary state of the landscape, distinguishing between youthful, mature, and old geomorphic stages (Pike & Wilson, 1971).

Hydrological controls are captured through **flow accumulation**, which expresses the total number of upslope cells draining into a given cell:

$$FA = \sum_{i=1}^{n} f_i$$

This parameter is essential for identifying preferential drainage pathways, runoff concentration zones, and potential initiation areas for erosion or channelized flow (Tarboton, 1997).

In risk mapping, flow accumulation is a key variable for delineating areas susceptible to concentrated surface runoff, gullying, and fluvial incision. It also plays a fundamental role in the identification of hydrologically active zones, particularly when integrated with slope gradient and topographic wetness index, significantly improving the prediction of erosion-prone and instability areas.

A key compound index is the **Topographic Wetness Index (TWI)**, which estimates the tendency of water to accumulate as a function of slope and contributing area:

$$TWI = \ln\left(\frac{a}{\tan(\beta)}\right)$$

where a is the specific catchment area **and tan β is the local slope angle. High** TWI values indicate zones potentially affected by saturation

excess, subsurface flow, and reduced slope stability (Beven & Kirkby, 1979).

Terrain heterogeneity is further represented by **terrain roughness**, commonly calculated as the local standard deviation of elevation values:

$$R = sqrt\left(\left(\frac{1}{n}\right) * sum_{i=1}^{n}(z_i - \bar{z})^2\right)$$

This metric reflects the irregularity of the surface and is often associated with structurally complex or highly dissected terrain (Hengl & Reuter, 2009).

Taken together, these parameters provide complementary information on terrain geometry, hydrological response, and morphodynamic behaviour. Their integrated use within a GIS-based framework allows a systematic representation of terrain susceptibility and provides the conceptual basis for subsequent methodological implementation in spatial risk modelling.

MATERIALS AND METHODS

1. Data

The methodological framework is based on the use of digital elevation models (DEMs) as the primary data source for terrain analysis. DEMs provide a continuous representation of the land surface, enabling the quantitative derivation of morphometric parameters that describe terrain geometry and its influence on geomorphological processes. The accuracy and spatial resolution of DEM data play a critical role in determining the reliability of derived parameters, as they directly affect the representation of slope gradients, curvature, and hydrological pathways (Moore et al., 1991; Wilson & Gallant, 2000).

High-resolution DEMs are preferred to capture fine-scale terrain variability and local geomorphological features. However, increasing resolution also amplifies noise and micro-topographic irregularities, which may introduce artifacts in derivative calculations. Consequently, preprocessing steps such as filtering, sink filling, and resampling are necessary to ensure data consistency and hydrological correctness prior to analysis (Tarboton, 1997; Hengl & Reuter, 2009).

Although the present study adopts a generalized methodological perspective, the framework is designed to be applicable to a wide range of DEM sources, including satellite-derived datasets (e.g., SRTM, ASTER) and higher-resolution LiDAR-based models, depending on data availability and the scale of analysis.

2. Derivation of Geomorphometric Parameters

Geomorphometric parameters are derived from DEM data using standardized GIS-based algorithms that operate on raster representations of elevation. The computation of first- and second-order derivatives is performed through finite difference methods applied to neighbouring cells, allowing the estimation of slope, aspect, and curvature under discrete conditions (Burrough & McDonnell, 1998).

Slope and aspect are typically calculated using 3×3 moving window operators, which approximate local gradients based on elevation differences between adjacent cells. Curvature parameters are derived from second-order derivatives and require careful numerical implementation to minimize sensitivity to DEM noise. Hydrological parameters, such as flow accumulation, are computed using flow routing algorithms, including deterministic approaches (D8) and more advanced methods (D∞), which provide improved representation of divergent flow conditions (Tarboton, 1997).

The Topographic Wetness Index (TWI) is calculated by combining slope and contributing area, requiring prior computation of flow direction and accumulation. Terrain roughness and relative relief are derived using neighbourhood-based statistical operations, which quantify local variability in elevation. Hypsometric analysis is conducted at the level of defined spatial units, typically drainage basins or grid-based partitions, allowing the characterization of elevation distribution and landscape evolution.

To ensure comparability between parameters, normalization procedures are applied, transforming variables into standardized ranges (e.g., 0–1). This step is essential for subsequent integration within multi-criteria models, as it eliminates scale-related biases and facilitates the weighting process (Malczewski, 2004).

3. GIS-Based Processing Workflow

The methodological workflow follows a structured sequence of operations designed to ensure reproducibility and consistency in terrain analysis. The process begins with DEM preprocessing, including sink filling to remove artificial depressions and ensure continuous flow routing. This step is essential for the correct computation of hydrological parameters and prevents the propagation of errors in downstream analyses (Tarboton, 1997).

Following preprocessing, geomorphometric parameters are systematically derived using dedicated GIS tools. The workflow integrates both surface-based and hydrological analyses, allowing the extraction of complementary terrain attributes that describe geometric configuration, flow dynamics, and structural variability. Each parameter is generated as a raster layer, maintaining spatial coherence and enabling subsequent overlay operations.

The derived variables are then standardized through normalization techniques, ensuring that all parameters are expressed on a comparable scale. This step is critical in multi-criteria environments, where variables with different units and ranges must be integrated without introducing disproportionate influence.

The final stage of the workflow involves the preparation of input layers for spatial modelling, including classification or reclassification of parameter values into susceptibility-relevant categories. This transformation facilitates the interpretation of terrain attributes in relation to geomorphological processes and enhances their applicability within risk assessment frameworks.

4. Multi-Criteria Spatial Modelling

The integration of geomorphometric parameters is performed using multi-criteria spatial modelling techniques, which allow the combination of multiple variables into a single susceptibility framework. This approach is particularly suitable for terrain analysis, where geomorphological processes are controlled by the interaction of several factors rather than a single dominant variable (Malczewski, 2004).

Each parameter is assigned a relative weight based on its theoretical relevance to geomorphological instability. Although weighting schemes may vary depending on the specific application, common approaches include expert-based evaluation and analytical hierarchy processes (AHP), which provide a structured method for comparing the relative importance of variables (Saaty, 1980).

The weighted parameters are aggregated using linear combination methods, resulting in a composite index that reflects the overall susceptibility of the terrain. The resulting values are subsequently classified into discrete categories (e.g., low, moderate, high susceptibility), enabling the delineation of zones with differentiated levels of geomorphological risk.

Given the absence of empirical validation in the present framework, the modelling approach is conceptual and focuses on methodological consistency rather than predictive performance. Nevertheless, the structure of the model allows for future integration of validation datasets, making it adaptable to applied studies.

RESULTS AND DISCUSSIONS

1. Conceptual Results and Analytical Interpretation

The proposed framework allows the formalization of terrain susceptibility as a multivariate function of geomorphometric parameters derived from DEM data. In the absence of empirical calibration, susceptibility is expressed through a composite scoring function based on normalized variables.

$$Sc = \Sigma(wi \cdot Xi, n), \quad \Sigma wi = 1$$

$$Sc = 0.20Sn + 0.05An + 0.10Cp, n + 0.10Cpl, n + 0.15FAn + 0.15TWIn + 0.10Rr, n + 0.10TRn + 0.05HIn$$

All variables are normalized using min.-max. transformation:

$$Xn = (X - Xmin.)/(Xmax. - Xmin.), \quad Xn \in [0.1]$$

The model structure highlights the dominant role of slope gradient, hydrological accumulation, and moisture distribution, which exert primary control on geomorphological instability. Slope influences shear stress and gravitational forcing, while flow accumulation and TWI control water concentration and pore-pressure conditions, which directly affect slope

stability (Beven & Kirkby, 1979; Moore et al., 1991).

Process-Based Sensitivity

The contribution of each parameter to susceptibility can be expressed through partial derivatives:

$$\partial Sc/\partial Xi = wi$$

indicating that model sensitivity is directly proportional to assigned weights. Thus, slope gradient and hydrological indices exert dominant control over susceptibility patterns.

Slope-dependent instability can be further related to shear stress:

$$\tau \propto \rho g h \sin(\theta)$$

which increases nonlinearly with slope angle, supporting the positive relationship:

$$\partial Sc/\partial S > 0$$

Hydrological Contribution

Hydrological influence is primarily captured through flow accumulation and the Topographic Wetness Index:

$$TWI = ln(a / tan\beta)$$

Increased soil moisture elevates pore-water pressure, reducing effective stress:

$$\sigma' = \sigma - u$$

resulting in decreased shear strength and increased susceptibility:

$$\partial Sc/\partial TWI > 0\,, \partial Sc/\partial FA > 0$$

Curvature Effects

Curvature parameters introduce second-order controls by regulating flow convergence and divergence, influencing sediment transport and local moisture distribution. Relative relief and terrain roughness quantify terrain energy and structural complexity, enabling the identification of highly dissected and potentially unstable areas (Strahler, 1952; Evans, 2012;).

The integrated behaviour of these variables defines susceptibility patterns as the result of nonlinear interactions rather than isolated effects. High susceptibility is associated with steep slopes, convergent topography ($Cpl < 0$), high flow accumulation, and elevated TWI values, while low susceptibility corresponds to gentle slopes, limited flow accumulation, and reduced terrain variability.

Although not empirically validated, the model demonstrates internal consistency and aligns with established geomorphological principles, supporting its applicability as a methodological framework for risk mapping (Reichenbach et al., 2018).

- $C_{pl} < 0$ - flow convergence → accumulation
- $C_{pl} > 0$ - flow divergence → dispersion

Profile curvature (C_p) regulates flow acceleration:

- $C_p < 0$ - deceleration and deposition
- $C_p > 0$ - acceleration and erosion

The integrated susceptibility behaviour can be expressed as:

$$Sc\ \alpha\ f(Cp, Cpl)$$

Morphostructural Controls

Relative relief and terrain roughness quantify terrain energy and structural complexity. Higher values indicate increased vertical dissection and surface irregularity, often associated with active geomorphological processes (Strahler, 1952; Hengl & Reuter, 2009).

$$\partial Sc/\partial Rr > 0\,, \partial Sc/\partial TR > 0$$

Integrated Susceptibility Behaviour

The model defines susceptibility as a nonlinear interaction between geometric and hydrological controls. High susceptibility occurs when slope, TWI and flow accumulation increase, while convergent flow conditions dominate.

Conversely, low susceptibility corresponds to low slope gradients, limited hydrological influence, and reduced terrain variability.

The integrated susceptibility behaviour can be expressed as:

$$Sc = f(G, H, M)$$

where: G = geometric component; H = hydrological component; M = morphostructural component.

Model Consistency

Although not empirically validated, the model exhibits internal mathematical consistency and aligns with established geomorphological process relationships. The functional relationships between variables reflect well-documented interactions between slope, hydrological accumulation, and terrain structure (Beven & Kirkby, 1979; Reichenbach et al., 2018).

2. Discussions

The proposed geomorphometric framework provides a coherent and reproducible methodological structure for terrain-based susceptibility assessment, emphasizing the integration of multiple morphometric variables within a unified analytical model. By formalizing terrain susceptibility as a function of normalized and weighted parameters, the approach ensures methodological transparency and facilitates its implementation within GIS environments.

A major strength of the framework lies in its ability to capture the interaction between geometric, hydrological, and morphostructural controls. Unlike approaches based on single-parameter analysis, the multi-criteria structure reflects the inherent complexity of geomorphological processes, where instability results from the combined influence of slope, moisture conditions, and terrain configuration. The explicit formulation of the susceptibility function enhances interpretability and allows for direct adaptation to different spatial contexts (Malczewski, 2004).

The use of DEM-derived parameters ensures broad applicability, as such data are widely available and can be processed consistently across different regions. Furthermore, the normalization of variables eliminates scale dependency, enabling the integration of heterogeneous datasets within a common analytical framework. This characteristic significantly improves the transferability of the methodology and supports its use in regional or comparative studies.

However, the absence of empirical validation represents a key limitation of the present approach. Without calibration against observed geomorphological events, the assigned weights remain theoretically grounded but not statistically optimized. As a result, the predictive performance of the model cannot be quantitatively assessed, and the susceptibility patterns should be interpreted as conceptual rather than definitive representations of risk.

Another limitation is related to the sensitivity of geomorphometric parameters to DEM resolution and quality. High-resolution datasets may introduce noise and micro-topographic variability, while low-resolution models may oversimplify terrain features, affecting the accuracy of derived indices such as curvature and flow accumulation (Hengl & Reuter, 2009). Additionally, the use of linear combination in the scoring function may not fully capture nonlinear interactions between variables, particularly in complex geomorphological settings.

Despite these limitations, the framework offers a robust basis for methodological development and can be readily extended through the incorporation of empirical datasets, statistical calibration techniques, or advanced modelling approaches. Future research should focus on integrating validation procedures, such as ROC analysis or inventory-based comparison, and exploring nonlinear or machine learning-based methods to enhance predictive capability.

From an applied perspective, the proposed methodology provides a valuable tool for preliminary risk assessment, land-use planning, and environmental management. Its structured and reproducible nature facilitates decision-making processes by offering a consistent approach to terrain evaluation, even in data-limited contexts.

CONCLUSIONS

The present study proposes a methodological framework for terrain morphological analysis based on DEM-derived geomorphometric parameters, aimed at supporting risk mapping applications. The approach integrates a comprehensive set of terrain attributes within a structured multi-criteria analytical model, enabling the systematic representation of geomorphological susceptibility.

By combining geometric, hydrological, and morphostructural variables, the framework provides a coherent interpretation of terrain behaviour, emphasizing the role of parameter interaction in controlling instability processes. The use of normalization and weighted aggregation ensures methodological consistency and facilitates the implementation of the model in GIS-based environments.

A key contribution of the study lies in the formalization of susceptibility as a quantitative function, which enhances transparency and reproducibility. The proposed structure allows for straightforward adaptation to different spatial contexts and can serve as a foundation for further methodological development.

Despite the absence of empirical validation, the framework demonstrates internal consistency and is grounded in established geomorphological and hydrological principles. However, the lack of calibration limits its direct predictive applicability, and the results should be interpreted as conceptual representations of susceptibility rather than definitive risk assessments.

Future research should focus on the integration of validation datasets, optimization of weighting schemes, and the exploration of nonlinear modelling techniques. The incorporation of statistical and machine learning approaches may further improve the predictive performance and adaptability of the model.

Overall, the proposed framework offers a scientifically robust and flexible basis for terrain analysis and risk mapping, with potential applications in land-use planning, environmental management, and disaster risk reduction.

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