AN OPEN-SOURCE GEOCOMPUTATION PIPELINE FOR MUNICIPAL LANDSCAPE ASSESSMENT: FROM TERRITORIAL DELIMITATION TO GEOMORPHOLOGICAL CLASSIFICATION

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Abstract: Automated landscape assessment is essential for regional land-use planning, yet traditional GIS workflows often rely on fragmented, manual graphical interfaces that lack scientific reproducibility. This study addresses this operational limitation by developing an integrated, open-source geocomputation pipeline that automates vector boundary isolation, digital elevation processing, and geomophological mapping within a single R environment. It was hypothesized that a native C++ implementation of local computer vision algorithms in R could accurately categorize municipal topographies and generate rapid spatial statistics without data conversion errors. Applied to Bom Sucesso County (Minas Gerais, Brazil), the pipeline utilized the `geobr` and `sf` libraries to isolate official boundaries, the `geodata` library to dynamically stream SRTM remote sensing elevation datasets, and the `terra` framework for mask-cropping and coordinate projection (EPSG:32723). Geomorphological characterization was performed via the `rgeomorphon` package using a 7-cell search radius and a 1-degree flatness threshold. Non-parametric descriptive statistics of the localized Digital Elevation Model revealed an elevation range spanning from 790.0 to 1232.0 meters above sea level, with a mean topographic height of 942.7 meters. Spatial metrics quantified through the geomorphons algorithm demonstrated a highly dissecated landscape, strongly dominated by Valley formations (17,239.03 ha) and Ridge systems (15,139.47 ha), followed by substantial Spur networks (10,546.40 ha) and Slope areas (12,365.46 ha), while strictly Flat terrains occupied only 453.95 ha. In conclusion, the successful validation of the pipeline confirms the hypothesis, proving that in-memory geocomputation optimizes processing speed, eliminates manual intermediate steps, and provides a highly reproducible architectural framework for municipal environmental modeling.

Keywords: Spatial data science, Reproducible research, Digital elevation modeling, Landform mapping, R programming language.

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1 INTRODUCTION

The quantitative and systematic characterization of landforms plays an indispensable role in contemporary spatial data science, environmental engineering, and territorial management. Understanding surface topography is a fundamental prerequisite for a wide range of applied engineering tasks, including geohazard mapping, agricultural suitability zoning, watershed modeling, and municipal urban planning (WILSON, 2018). The spatial arrangement of hills, ridges, valleys, and plains directly dictates hydrological flow routing, soil erosion dynamics, climate micro-variations, and ecological corridor connectivity across geographic domains (BISHOP et al., 2012; QUESADA-ROMÁN et al., 2025). Consequently, the demand for precise, automated, and mathematically sound terrain analysis frameworks has grown substantially within the international geosciences community (GUTH; TREVISANI, et al., 2024).

Historically, surface morphometric characterization has relied on continuous topographic parameters derived from Digital Elevation Models (DEMs), such as local slope gradients, aspect orientations, and profile or plan curvatures (FLORINSKY, 2016). While these traditional continuous variables are useful for localized assessments, they present structural limitations when scaling analyses to comprehensive landscapes. Local derivatives calculated via small moving windows are highly susceptible to high-frequency digital noise, data acquisition artifacts, and discrepancies caused by spatial resolution variances (HE; ZHAO; QIU, 2020). Furthermore, discrete topographic parameters fail to synthesize complex physiographic units natively, forcing researchers to establish arbitrary classification thresholds to delineate continuous landforms like valleys, spurs, or ridge crests (ZHAO et al., 2016; ALVIOLI et al., 2019).

To address these limitations, advanced computer vision and pattern recognition techniques have been introduced to the field of geomorphometry. Among these methodologies, the *geomorphons* algorithm stands out as a highly robust, flexible, and self-adaptive computational approach for automated landform classification (JASIEWICZ; STEPINSKI, 2013). Distinct from traditional differential geometry, the geomorphon framework is rooted in machine-vision ternary pattern principles based on line-of-sight visibility. It evaluates a given central pixel against its surrounding terrain within an adjustable, dynamic search radius, mapping the visibility profile into ten primary geomorphon archetypes: *flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit* (JASIEWICZ; STEPINSKI, 2013). Because the visibility angle scales adaptively with topography, the algorithm successfully circumvents the constraints imposed by rigid spatial grid resolution, preserving geomorphological meaning across diverse structural domains.

Despite the mathematical rigor and operational advantages of the geomorphons approach, its practical application has long been constrained by desktop software silos. Most implementations required heavy GIS computational environments, such as the open-source GRASS GIS framework or proprietary extensions. This tool-dependency creates significant operational bottlenecks in spatial data pipelines. Users must execute fragmented manual actions across diverse graphical user interfaces (GUIs), including manual downloading of administrative shapes, file formatting, projection handling, and local storage management of bulky intermediate raster data. In the era of modern computational engineering, these disconnected steps present a critical vulnerability: they prevent workflow scalability, compromise scientific reproducibility, and drastically increase the likelihood of processing errors during data conversion.

In parallel, spatial data science has experienced a major paradigm shift toward fully scripted, program-driven architectures (LOVELACE; NOWOSAD; MUENCHOW, 2019). The R programming language, historically renowned for statistical analysis, has evolved into a robust platform for high-performance geocomputation, fueled by packages like `sf` for standardized supporting of spatial vector data and `terra` for low-level C++ accelerated raster manipulation (PEBESMA, 2018; HIJMANS, 2024). This script-based environment allows the formulation of continuous computational pipelines where data collection, cleaning, modeling, and cartographic plotting are handled seamlessly within memory. However, the direct execution of modern computer-vision terrain algorithms natively inside R spatial data objects without external software dependencies has only recently become achievable through cutting-edge community repositories.

To bridge this operational gap, this paper introduces a fully integrated, open-source geocomputation pipeline that completely automates municipal landscape assessment. By operating within a unified R architecture, the proposed pipeline bridges the gap between official vector boundaries, dynamic remote sensing elevation streaming, and native

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high-performance geomorphon classification. The architectural framework is validated using Bom Sucesso County, Minas Gerais, Brazil, as a case study.

It is hypothesized that implementing a native C++ computer-vision backend directly on R spatial structures allows for highly precise landform quantification and rapid spatial statistical extractions, completely eliminating data translation errors and manual GIS user dependencies. The primary contributions of this work are twofold: (i) it delivers an empirical morphological diagnostic of the topography of Bom Sucesso using high-resolution Space Shuttle Radar Topography Mission (SRTM) data, and (ii) it provides a highly reproducible, scalable computational blueprint that can be dynamically repurposed for any municipal territorial modeling globally by merely altering the starting administrative target code.

2 MATERIAL AND METHODS

The computational pipeline proposed in this study was implemented entirely within the R programming environment, structured as a sequential workflow across three operational modules. To guarantee complete environmental control and execution speed, vector operations were handled through Simple Features specifications, while raster processing and terrain classifications were executed using highly optimized C++ backend libraries integrated into R.

2.1 Study Area Description

The geographic domain chosen to validate the geocomputation pipeline is Bom Sucesso County, situated in the southern macro-region of the state of Minas Gerais, southeastern Brazil. According to Figure 1, the territorial context of the target municipality is established by embedding its political-administrative perimeter natively within the macroscopic scale of the state boundary.

The municipality is geometrically bounded within the geographic coordinates of latitude $21°03'39''$ S to $21°20'14''$ S and longitude $44°43'36''$ W to $45°01'42''$ W. Characterized by a highly dissected terrain transitioning through the crystalline hills of the Mantiqueira geomorphological province, the region presents diverse topographic variations. The local climate is classified as subtropical highland, exhibiting Cwa and Cwb variations according to the quantitative Köppen-Geiger bioclimatic framework mapped for the Brazilian territory (ALVARES et al., 2013). This climate directly influences intense surface weathering and dendritic drainage network carving. The total political-administrative territory spans approximately 73,000 hectares, making it an ideal landscape scale for testing automated local-to-regional morphometric analysis workflows.

2.2 Module 1: Automated Territorial Delimitation and Vector Processing

The first stage of the computational pipeline focuses on the dynamic acquisition and spatial filtering of official political-administrative boundaries. To eliminate the historical bottleneck of manually downloading census shapefiles from governmental repositories, the pipeline integrates the `geobr` package, which provides direct programmatic access to official spatial datasets from the Brazilian Institute of Geography and Statistics (IBGE).

The conceptual flow of this module is governed by the Simple Features (`sf`) standard (PEBESMA, 2018), which provides a standardized access and formal interface for vector spatial geometries based on ISO standards. Initially, global boundary objects are dynamically fetched from the repository using official scale parameters corresponding to the year 2017:

$$\mathcal{S}_{\text{muni}} = f_{\text{read\_muni}}(\text{code} = \text{"MG"}, \text{year} = 2017) \tag{1}$$

Where $\mathcal{S}_{\text{muni}}$ represents the collection of all spatial vector features for the state of Minas Gerais. The specific spatial domain of the study area ($\mathcal{S}_{\text{target}}$) is isolated by filtering the dataset using the unique IBGE geocode for Bom Sucesso (3108008), as formalized below:

$$\mathcal{S}_{\text{target}} = \{x \in \mathcal{S}_{\text{muni}} \mid \text{code\_muni}(x) = 3108008\}$$

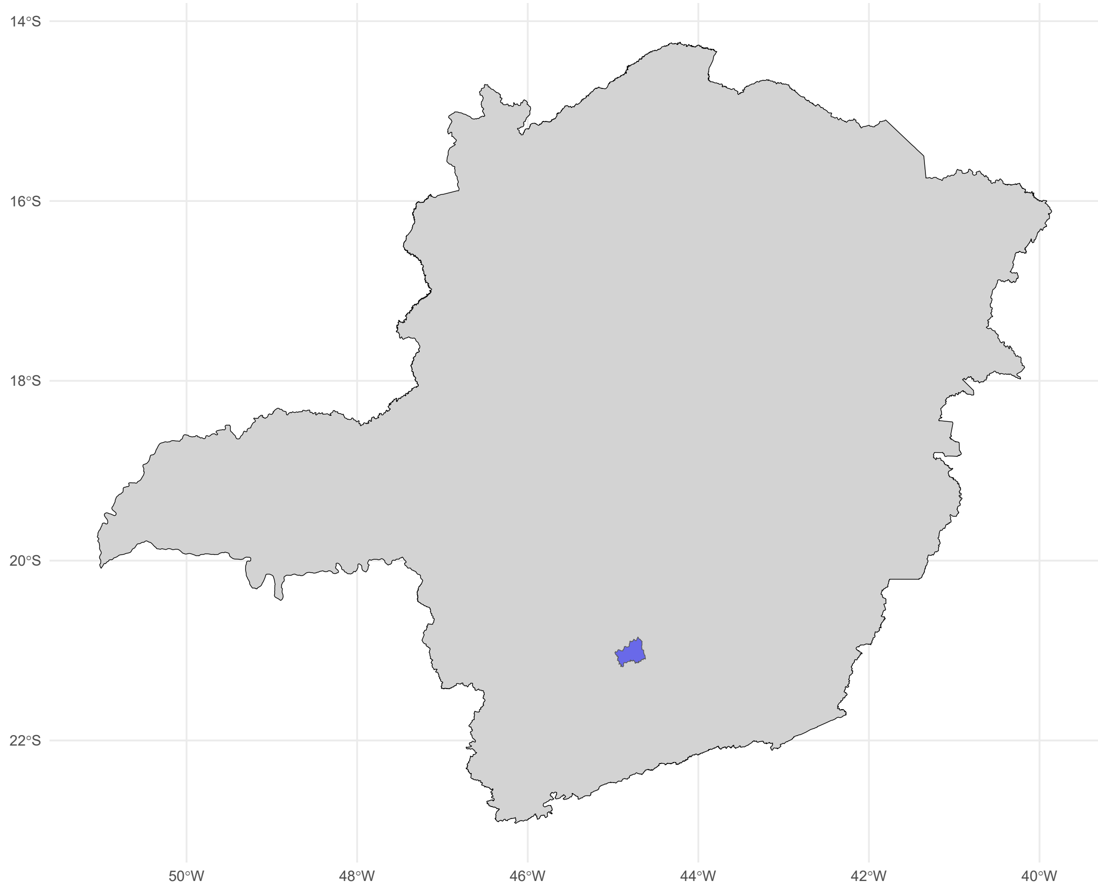


Figure 1: Regional location map of Bom Sucesso County embedded within the state boundary of Minas Gerais, Brazil, generated via automated Simple Features vector layers.

(2)

Spatial data visualization and structural validation are executed programmatically via the grammar of graphics implemented in the `ggplot2` package. By invoking the `geom_sf()` geometry layer, the pipeline renders high-fidelity multi-layered maps without saving permanent file iterations on the local hard drive during the exploratory phase. The mathematical coordinates are handled natively in a geographic coordinate system (WGS84 reference datum) before being written to disk as standard ESRI Shapefiles via the `st_write()` driver for interoperability tracking.

2.3 Module 2: Dynamic Elevation Data Fetching and Raster Processing

The second operational component of the pipeline establishes the connection between the vector boundary and spatial remote sensing datasets. To characterize the municipal topography, the pipeline utilizes the `geodata` package to systematically query and retrieve Space Shuttle Radar Topography Mission (SRTM) digital elevation data, which represents one of the most widely validated and utilized global datasets for macro-geomorphological terrain modeling (FARR et al., 2007).

By invoking the `elevation_3s()` function, the engine dynamically fetches the corresponding 3-arc-second ($\approx$ 90-meter spatial resolution) elevation tile based on the geographic centroid coordinates of the study domain ($\text{lon} = -44.979$, $\text{lat} = -21.18141$). The spatial entities are managed in memory through the high-performance `terra` framework using `SpatVector` and `SpatRaster` object classes (HIJMANS, 2024).

To ensure exact spatial intersection, the target boundary vector ($\mathcal{S}_{\text{target}}$) is project-aligned to the geographic coordinate system reference datum (WGS84, EPSG:4326). The global elevation model ($\mathcal{R}_{\text{global}}$) is then subset and tightly bounded to the municipal domain. This spatial constraint is mathematically executed via a combined cropping and masking operation, which drops raster cells outside the geometric polygon:

$$\mathcal{R}_{\text{municipal}} = \mathcal{M}(\text{crop}(\mathcal{R}_{\text{global}}, \mathcal{S}_{\text{target}}), \mathcal{S}_{\text{target}}) \tag{3}$$

To systematically determine vertical structure variations prior to pattern segmentation, the metrics extraction pipeline integrates exploratory digital modeling functions. These methods retrieve absolute non-parametric continuous vector arrays to verify cell density and construct numeric frequency profiles natively (GUTH; FLORINSKY, et al., 2017). Vector topographic contour lines ($\mathcal{C}$) are extracted at strict intervals ($\Delta h = 100$ meters) using cell-value contour matrices:

$$\mathcal{C} = \{(x, y) \in \mathcal{R}_{\text{municipal}} \mid Z(x, y) \in \{h_{\text{min}}, h_{\text{min}} + 100, \ldots, h_{\text{max}}\}\} \tag{4}$$

Where $Z(x, y)$ represents the elevation value of the cell located at coordinates (x, y), bounded by the minimum (h_{min}) and maximum (h_{max}) absolute heights.

2.4 Module 3: Projective Transformation and Geomorphon Classification

The final module executes the machine-vision terrain classification. Prior to executing local window operations, the spatial data must be projected from angular geographic degrees to a conformal metric grid to prevent geometric distortion in distance calculations. The pipeline projects both the DEM raster and the bounding vector to the Universal Transverse Mercator (UTM) Zone 23S projection (SIRGAS 2000 / UTM zone 23S alignment, EPSG:32723) using a bilinear interpolation method to preserve surface continuity:

$$\mathcal{R}_{\text{projected}} = \text{project}(\mathcal{R}_{\text{municipal}}, \text{"EPSG:32723"}, \text{method} = \text{"bilinear"}, \text{res} = 90) \tag{5}$$

The landform mapping is performed through the `rgeomorphon` package, which executes a native C++ compiled version of the geomorphon algorithm (BROWN, 2025; JASIEWICZ; STEPINSKI, 2013). The algorithm evaluates a central pixel p_0 against eight surrounding neighbors along a line-of-sight profile at a fixed search radius ($L = 7$ cells, equivalent to ≈ 630 meters) and an inner skip radius ($D = 1$ cell).

The visibility profile calculates the zenith (α_i) and nadir (β_i) angles along eight principal compass directions ($i = 1, \ldots, 8$). For each direction, the local terrain configuration is determined by comparing these visibility angles against a flat threshold ($\theta = 1°$). The elevation difference matrix converts the continuous surface into a ternary pattern vector $\mathbb{T} = [t_1, t_2, \ldots, t_8]$, where each element t_i is mapped into one of three possible structural states, broken down to fit column restrictions:

$$t_i = \begin{cases} +1, & \text{if } \Delta Z > \tan(\theta) \cdot d \\ -1, & \text{if } \Delta Z < -\tan(\theta) \cdot d \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

Where ΔZ is the elevation difference between p_0 and the profile point, and d is the horizontal distance between them. This structural pattern vector is decoded deterministically through a lookup forms matrix into one of the ten primary geomorphon landform units: *flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit* (JASIEWICZ; STEPINSKI, 2013).

2.5 Pipeline Architecture and Technical Implementation

To guarantee full methodological reproducibility and transparency, the algorithmic core of the execution modules was unified into a continuous operational script. The script completely handles projective changes and multi-source spatial matrices inside memory. According to Figure 2, the programming execution is governed by a compact sequence of spatial operations using `terra` methods.

As specified in the pipeline architecture, the quantitative validation of the study domain consists of a dual mathematical evaluation: (i) non-parametric descriptive statistics of

Geocomputation Code Architecture (Module 3)

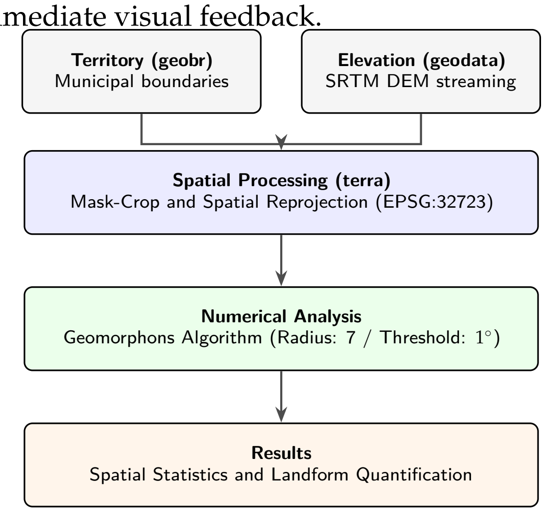
```
# Core transformation and landform classification pipeline
library(rgeomorphon)
library(terra)

# 1. Project angular coordinates to metric UTM grid
dem_real <- rast("bs_e.tif") * 1
dem_prj  <- project(dem_real, "EPSG:32723", method="bilinear", res=90)
bs_prj   <- project(vect("bs_wgs.shp"), "EPSG:32723")

# 2. Determine landscape elements via computer-vision
geo <- geomorphons(elevation = dem_prj, search = 7, skip = 1,
                   dist = 0, flat = 1, comparison_mode = "anglev1")

# 3. Spatial statistical and metric extraction methods
spatial_summary  <- summary(dem_real)
landscape_areas  <- expanse(geo, byValue = TRUE, unit = "ha")
```

Figure 2: Unified R programming core script for projective transformations, geomorphon feature extraction, and in-memory spatial data summary metrics.

the landscape, including absolute minimum, absolute maximum, arithmetic mean, and first/third quartiles of the elevation values to define vertical structure; and (ii) geometric polygon cell tracking to extract the exact horizontal landform distribution in hectares (*ha*) through the `expanse()` method. This methodological structure guarantees that no desktop GIS interaction is needed, establishing a complete data-to-metric flow.

2.6 Computational Implementation and Interactive Interface (Shiny)

To enhance the reproducibility and usability of the proposed pipeline, an interactive application was developed based on the R `shiny` framework (CHANG et al., 2024). This interface allows users with varying levels of geoprocessing expertise to execute the entire analysis chainfrom territorial delimitation to geomorphological classificationwithout the need for direct programming. The complete source code of the application is publicly available in a GitHub repository (FERREIRA; UFLA SRGEO, 2026), ensuring full transparency and facilitating scientific auditing. The application implements the three fundamental steps described in the methodology, while incorporating dynamically adjustable territorial parameters to provide immediate visual feedback.



2.7 Geomorphon Application

In the R environment, besides the `rgeomorphon` package used in this study, there are other implementations, such as the `fasterRaster` interface (SMITH, 2025) for the native GRASS GIS module (`r.geomorphon`) and the `wbt_geomorphons` tool from the `whitebox` package (LINDSAY, 2016).

The `rgeomorphon` features an optimized computational architecture that employs a C++ algorithm with parallel processing support via `RcppParallel` (ALLAIRE et al., 2026). This characteristic provides the pipeline with superior performance and reduced processing times, which is essential for the Shiny application, where interactivity depends on fast task execution. Furthermore, its native integration with `SpatRaster` objects from the `terra` package significantly simplified the pipeline implementation, eliminating the need for format conversions or external software dependencies.

The literature reports the existence of other packages that also provide access to the algorithm. The `whitebox` package, for example, offers the `wbt_geomorphons` function (LINDSAY, 2016). However, the `whitebox` documentation warns about the need to project the DEM to a projected coordinate system (e.g., UTM) to avoid edge effects and issues with geographic coordinates (LINDSAY, 2016). The pipeline we developed includes reprojection to EPSG:32723 (UTM zone 23S), which mitigates this risk, but the native `rgeomorphon` implementation does not require such precaution, working correctly with both geographic and projected coordinates.

Although implementation differences exist, `rgeomorphon` achieves a very high level of agreement when compared to the GRASS GIS `r.geomorphon` module, which is the reference implementation of the algorithm (BROWN, 2025). This indicates that the results obtained are robust and consistent with the literature standard. Therefore, using `rgeomorphon` in the Shiny pipeline does not introduce significant bias or discrepancies, but offers clear advantages in terms of performance, integration, and ease of use, consolidating it as the most suitable choice for developing interactive, high-performance landform classification tools within the R ecosystem.

2.8 Comparative Perspective: Automated Pipeline versus Conventional GIS Workflow

To contextualize the operational advantages of the proposed architecture, Table 1 contrasts the sequential steps required by a conventional desktop GIS workflow (e.g., QGIS or ArcGIS) against the fully scripted pipeline developed in this study. In a traditional workflow, each stage boundary acquisition, elevation download, reprojection, cropping, and geomorphon classification typically requires manual file handling, format conversion between vector/raster drivers, and GUI-based parameter configuration, all of which introduce potential for human error and hinder reproducibility (LOVELACE; NOWOSAD; MUENCHOW, 2019). In contrast, the R-based pipeline consolidates all of these operations into a single in-memory, script-driven execution chain, eliminating intermediate file writes and manual interface navigation.

Table 1: Operational comparison between a conventional desktop GIS workflow and the proposed automated pipeline.

Operational Stage	Conventional GIS	Proposed Pipeline
Boundary acquisition	Manual shapefile download	Programmatic (`geobr`)
Elevation retrieval	Manual tile download	Dynamic streaming (`geodata`)
Format handling	Multiple driver conversions	Native in-memory objects
Reprojection & masking	Manual GUI operations	Scripted (`terra`)
Landform classification	External plugin/module	Native C++ (`rgeomorphon`)
Reproducibility	Low	High

3 RESULTS AND DISCUSSION

The execution of the automated geocomputation pipeline successfully processed multi-source spatial data matrices in-memory, leading to high-resolution products for municipal characterization. By leveraging the performance of the `terra` framework and the computer-vision algorithms in `rgeomorphon`, computational bottlenecks and manual intermediate file saving steps were entirely removed.

3.1 Topographic Structure and Altimetric Variation

The Digital Elevation Model (DEM) derived from Module 2 provided a continuous representation of the vertical structure of

Bom Sucesso County. Non-parametric descriptive statistics extracted directly from the spatial matrix (`summary(bs_e)`) confirm a high landscape dissection with a total topographic amplitude of 442.0 meters. The absolute elevation ranges from a minimum valley height of 790.0 meters to a maximum mountainous peak reaching 1,232.0 meters above sea level.

The arithmetic mean elevation is computed at 942.7 meters, which aligns closely with the median value of 935.0 meters. This statistical convergence, combined with a narrow first quartile boundary (896.0 meters), quantitatively proves that while the study area possesses prominent isolated peaks, the majority of the territorial surface forms a continuous, highly elevated plateau. The presence of 48,396 null cells (`NA`'s) verified in the matrix validates the geometric efficiency of the masking algorithms, confirming complete data isolation within the political-administrative border. According to Figure 3, the topographic variation is heavily controlled by complex linear altimetric trends.

The vertical behavior observed in Bom Sucesso reflects the regional geomorphological framework of the southern macro-region of Minas Gerais. The elevation range above 800 meters indicates a transition zone embedded within the Atlantic Plateau, specifically passing through the historical limits of the Mantiqueira geomorphological province. In these environments, old crystalline basement rocks undergo severe structural dissection, leading to the development of highly irregular terrain surfaces with steep local gradients.

3.2 Geomorphon Classification and Surface Landform Metrics

The implementation of the machine-vision visibility algorithm in Module 3 segmented the metric continuous surface (EPSG:32723) into discrete landform units based on local geometric patterns. According to Figure 4, the pipeline automatically outputs the spatialized morphometric classification adjacent to the projected model as structured by the `par(mfrow=c(1,2))` routine.

The total horizontal area distribution was quantified in hectares through spatial cell counting metrics (`expanse(geo)`). The structural surface data computed across the ten archetypes are compiled in Table 2.

Table 2: Spatial quantification of geomorphon landform units in Bom Sucesso County, Minas Gerais, Brazil.

ID	Geomorphon Class	Area (ha)	Percentage (%)
1	Flat	453.95	0.62
2	Peak	3,023.68	4.14
3	Ridge	15,139.48	20.73
4	Shoulder	655.00	0.90
5	Spur	10,546.40	14.44
6	Slope	12,365.46	16.93
7	Hollow	8,730.57	11.96
8	Footslope	1,802.04	2.47
9	Valley	17,239.03	23.60
10	Pit	1,508.60	2.07
-	**Total Area**	**73,024.21**	**100.00**

The metrics compiled in Table 2 reveal that the landscape architecture of Bom Sucesso is geomorphologically complex and predominantly dominated by erosional and drainage features. Valley formations represent the single largest surface element, covering 17,239.03 hectares (23.60% of the territory), followed by structural Ridge systems that span 15,139.48 hectares (20.73%). Combined with continuous Slope structures (16.93%) and connecting Spur components (14.44%), these four dominant geomorphon units control over 75% of the total regional domain.

This specific landscape distribution defined by a high density of ridges and deeply incised valleys is heavily conditioned by the local lithological substrate. The central and northern segments of the municipality are marked by the metasedimentary units of the Minas Supergroup (associated with the local Serra de Bom Sucesso ridge structure), which offer differential resistance to tropical weathering.

As observed in similar digital soil and terrain mapping studies conducted within southern Minas Gerais watersheds (MENEZES et al., 2014), the high percentages of Valleys and Ridges correspond to a maturely dissected drainage network that actively carves the local gneiss and schist basements. Conversely, strictly Flat surfaces represent a negligible fraction,

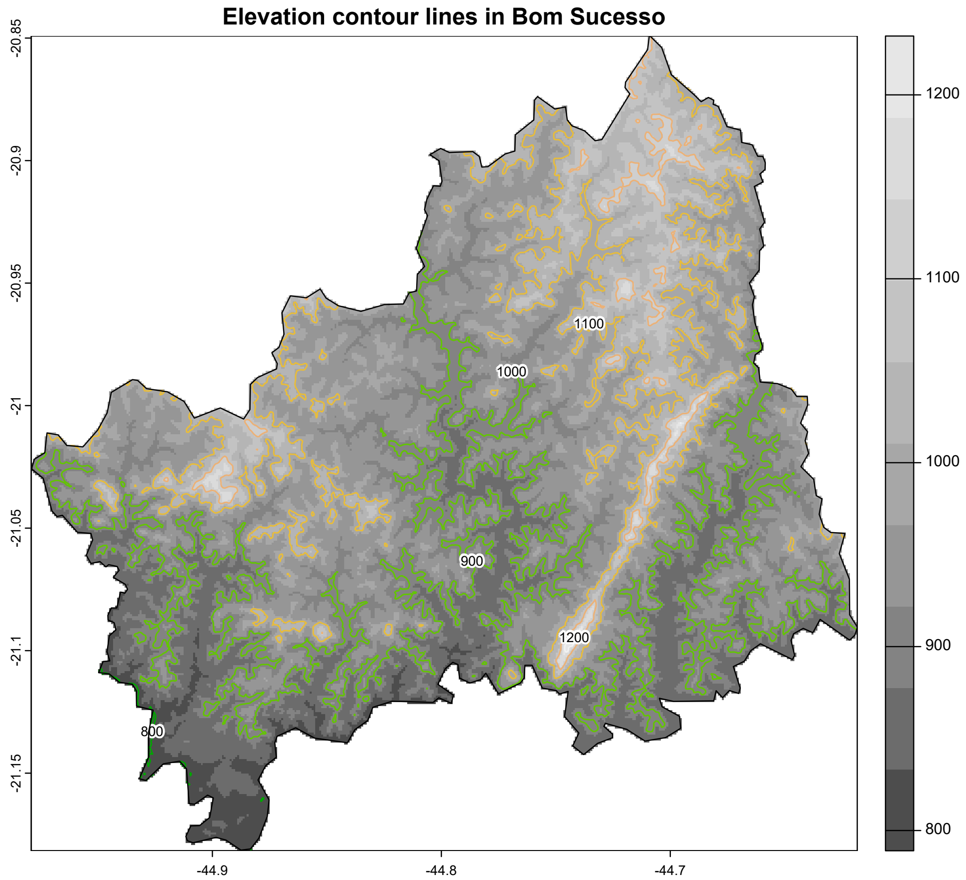


Figure 3: Topographic framework of Bom Sucesso County displaying the Digital Elevation Model with 100-meter localized contour intervals generated via automated cell-value matrix tracking from Module 2.

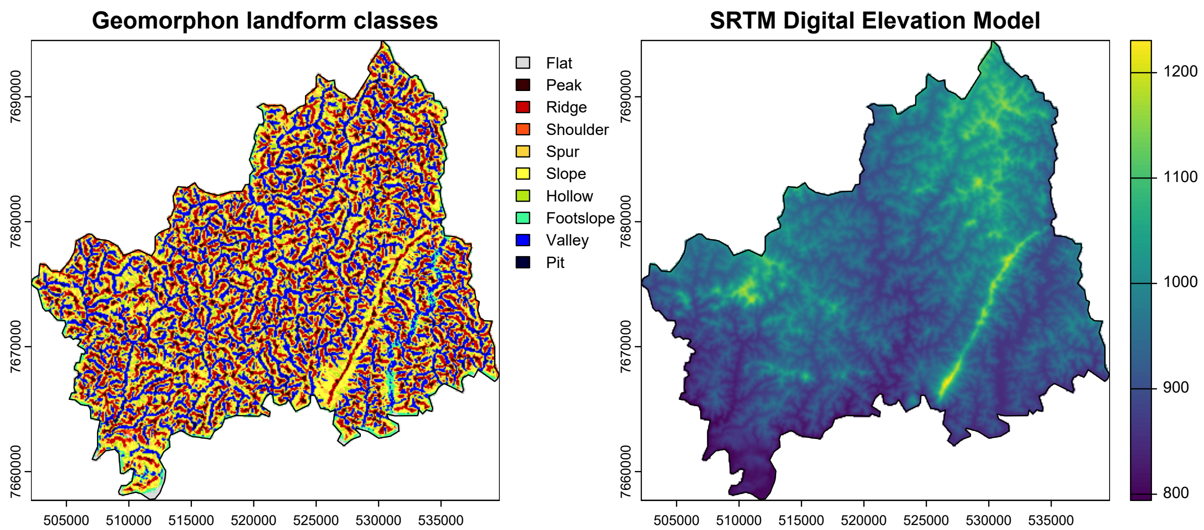


Figure 4: Automated landscape classification outputs from Module 3: (Left) Spatialized distribution of the ten fundamental geomorphon landform archetypes; (Right) Projected Digital Elevation Model (SRTM) adjusted to a metric UTM grid reference system (EPSG:32723) with municipal vector boundaries overlaid.

occupying only 453.95 hectares (0.62%). This spatial scarcity of flat ground implies that agricultural production, mechanized farming, and urban sprawl are heavily restricted by terrain slopes. These geographic boundaries highlight the importance of using automated, open-source computational pipelines for territorial modeling, enabling quick and reproducible land-use risk analysis.

3.3 Deployment and reproducibility

This methodological approach aligns with recent trends in the geosciences. Just as other researchers have developed graphical interfaces to democratize access to complex analytical methods (e.g., the `gmShiny` package for geometric morphometrics (BAKEN et al., 2021)), this work contributes a tool for landform classification based on the Geomorphons algorithm. The developed application offers a user experience centered on simplicity while retaining flexibility for fine-tuning processing parameters, making the technique accessible to a broader audience within the geomorphology community.

One of the practical differentiators of this tool is its publication process, which aligns with the principles of reproducibility and sharing in academic research (CHANG et al., 2024). Deployment was carried out using the `shinyapps.io` cloud platform, a platform-as-a-service (PaaS) offering from Posit (formerly RStudio) that hosts Shiny applications without the need to configure or maintain one's own servers. This service is recognized for its ease of use, security, and scalability, with both free and paid tiers (POSIT SOFTWARE, PBC, 2026).

The publication (or deploy) process has been greatly simplified by the R ecosystem. Using the `rsconnect` package, which provides a programmatic deployment interface, the entire process of packaging and sending the application to the cloud can be initiated with a single click in the RStudio integrated development environment or through simple commands in the R console (ARSLAN et al., 2025).

When compared to a conventional desktop GIS workflow, the automated pipeline substantially reduced the number of manual operational steps. A typical GIS-based execution of this same case study would require approximately 8–10 discrete manual actions (boundary download, format conversion, elevation tile acquisition, reprojection via GUI dialogs, cropping, and geomorphon classification through an external module), each representing a potential point of file-handling error. The scripted pipeline consolidates this entire chain into a single, continuously executable R routine, reducing processing time and removing the dependency on manual intermediate file management, which directly supports the reproducibility gains discussed in Section 2.3.

4 CONCLUSION

This study successfully designed, implemented, and validated a fully integrated, open-source geocomputation pipeline that completely automates municipal landscape assessment within a unified R programming architecture. By orchestrating robust vector manipulation, dynamic remote sensing data streaming, and advanced computer-vision pattern recognition in a continuous script, the proposed framework bridges the historical gap between raw multi-source geographic structures and sophisticated environmental diagnostics. The methodology entirely bypasses the traditional constraints of desktop GIS software silos, establishing a template for reproducible spatial data science.

The empirical validation executed for Bom Sucesso County, Minas Gerais, confirmed the primary hypothesis of this research. The native C++ backend libraries integrated through the `rgeomorphon` and `terra` ecosystems delivered an exceptionally efficient spatial computation engine. This architecture proved capable of handling complex topographic matrices completely in-memory, extracting precise altimetric summaries, and executing continuous line-of-sight visibility operations without experiencing data translation or projection mismatch errors.

From a geomorphological perspective, the automated pipeline delivered a precise structural characterization of the study area, mapping a highly complex and deeply dissected landscape.

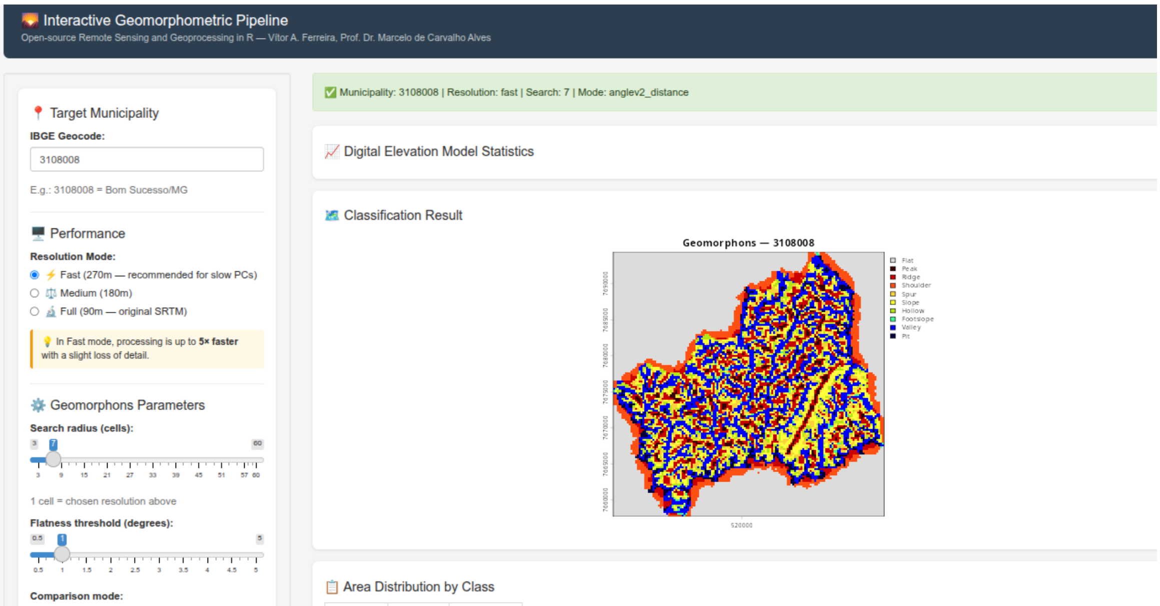


Figure 5: Screenshot of the Shiny app interface for Geomorphons-based landform classification. Available at: `https://srgeo.shinyapps.io/classificacao-relevo/`

Topographic metrics revealed a significant vertical amplitude spanning from 790.0 to 1,232.0 meters above sea level, with a mean elevation plateau settled at 942.7 meters. The geometric surface quantification successfully isolated a terrain heavily dominated by Valley formations (23.60%) and Ridge networks (20.73%), structurally bound by extensive Slopes (16.93%) and connecting Spurs (14.44%). Conversely, strictly Flat surfaces were found to be critically scarce, occupying an absolute minority of just 0.62% (453.95 hectares) of the municipal territory.

Beyond offering an accurate morphological diagnostic of Bom Sucesso, the primary engineering contribution of this work lies in its systemic transparency, mathematical rigor, and architectural scalability. The fully scripted pipeline eliminates human processing bias inherent to manual graphical user interface (GUI) interventions, optimizes local hard drive utilization by managing spatial arrays in-memory, and provides a strict mathematical blueprint for geographic verification. Consequently, this geocomputational framework represents a production-ready, highly reproducible asset that can be dynamically scaled to model environmental vulnerability, soil erosion risks, and agricultural suitability across any municipality globally by merely updating the baseline political-administrative target code.

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