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# High-resolution Digital Terrain Model and Land-surface Parameters of São Sebastião and Ilhabela, southeastern Brazil

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## Abstract

Effective disaster risk management and detailed environmental studies in landslide-prone regions require high-resolution and accurate Digital Terrain Models (DTMs). This work describes the development of a 2 m-resolution lidar-based DTM and an extensive set of land-surface parameters (LSPs) for the municipalities of São Sebastião and Ilhabela, southeastern Brazil. The dataset was generated from approximately 650 GB of airborne lidar point clouds, processed through a reproducible workflow comprising ground point classification, merging of filtered files, Triangulated Irregular Network (TIN) interpolation, gap filling, and surface smoothing. The resulting high spatial resolution enabled the extraction of topographic parameters for local-scale landslide susceptibility analyses, surpassing the detail of existing photogrammetric and global DEMs for the region, revealing geomorphological features previously indiscernible, including past landslide deposits, drainage captures, and structural lineaments. The resulting products represent the first openly accessible high-resolution DTM for this region, made available via Zenodo, thus supporting applications in landslide susceptibility mapping, environmental modeling, and territorial planning. This open-access initiative contributes to bridging the gap in Brazil's high-resolution topographic data availability and fosters both scientific research and evidence-based decision-making.

*Keywords:* lidar, geomorphometry, geomorphology, landslide, tectonics, territorial planning

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## 1. Introduction

Digital Elevation Models (DEMs) are ubiquitous datasets in science to represent Earth's surface. More specifically, a Digital Surface Model (DSM) marks the lower boundary of the atmosphere (with the terrain, water bodies, ice, vegetation or human-made objects), while a Digital

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Terrain Model (DTM) records the boundary between the terrain (lithosphere) and the atmosphere, without vegetation, buildings etc, also being called a “bare-earth” DEM (Guth *et al.*, 2021).

DEMs can be generated by various means such as InSAR (Interferometric Synthetic Aperture Radar), photogrammetry of optical imagery, and lidar (light detection and ranging), with terrestrial, airborne, or spaceborne sensors (Nelson *et al.*, 2009). Photogrammetry always produces DSMs, since optical images cannot provide information below the canopy (Winsen & Hamilton, 2023). InSAR can produce DSMs or DTMs, depending on the wavelength employed; longer wavelengths may penetrate foliage but shorter wavelengths will be reflected at the top or mid-canopy. Time of data acquisition will also influence the results, due to loss of foliage in temperate forests during autumn (allowing more signal penetration even with shorter wavelengths) or snow coverage in winter (Carabajal & Harding, 2006). Lidar can also produce DSMs or DTMs, as the sensors can register several reflections of the same emitted laser pulse, from the top of canopy, to intermediate objects, through the ground (Fowler *et al.*, 2007).

There are several global (or quasi-global) DEMs available at no cost to the user, such as SRTM (Shuttle Radar Topography Mission – Farr *et al.*, 2007), ASTER GDEM (ASTER Global DEM – Tachikawa *et al.*, 2011), ALOS AW3D30 (ALOS World 3D – Tadono *et al.*, 2015), and Copernicus DEM (CopDEM – Strobl, 2020), all distributed at a resolution of 1 arc-second ( $\approx 30m$  at the Equator). These are all considered as DSMs due to their methods of generation (InSAR for SRTM and Copernicus DEM, photogrammetry for ALOS AW3D30 and ASTER GDEM), although SRTM and CopDEM show elevations closer to mid-canopy in some regions (Carabajal & Harding, 2006; Guth & Geoffroy, 2021). Recently, several endeavors have been presented to create DTMs with machine learning methods, based on the global DSMs and ancillary data (local lidar data, land-use maps, etc.). These ‘edited DEMs’ include FABDEM (Hawker *et al.*, 2022), FathomDEM (Uhe *et al.*, 2025) and GEDTM (Ho *et al.*, 2025) with full global coverage, as well as DeltaDTM (Pronk *et al.*, 2024) and DiluviumDEM (Dusseau *et al.*, 2023), which focus on coastal areas.

Country-wide DEMs are commonly based on lidar or photogrammetry of high-resolution orbital or airborne imagery. Examples include the USGS 3D Elevation Program (3DEP), which provides a lidar-based multi-resolution dataset at resolutions of approximately 30, 10 and 3 meters for the conterminous United States and at 1 m for parts of the United States<sup>1</sup>; most European countries offer open access to lidar-based DEMs, as well as New Zealand; Mexico has 1 m and 5 m lidar DEMs for several areas of the country.

Brazil is a country of continental dimensions, but lacks detailed topographic mapping of its territory. Currently, the Federal agency responsible for systematic mapping, IBGE (*Instituto Brasileiro de Geografia e Estatística* – Brazilian Institute for Geography and Statistics), indicates that 100% of the territory is mapped at a 1:250,000 scale, 70% at a 1:100,000, 15% at a 1:50,000, and only 1% at 1:25,000<sup>2</sup>.

In the 2010s, a joint initiative of the Brazilian Army and Air Force sought to fill the Amazonian ‘cartographic void’ (areas with mapping at 1:250,000 or less) with airborne InSAR in a project known as ‘Radiography of Amazonia’ (RAM) (Grohmann, 2015). The resulting available data are 5 m DSMs distributed under a restrictive license (the data are considered sensitive and cannot be shared with foreign researchers, for example) through the Army’s Geoportal<sup>3</sup>. Initially, there was also availability of DTMs and raw radar images, but that data is now of exclusive use of the Brazilian Armed Forces.

In Brazil, each state is responsible for topographic mapping at scales of 1:10,000 or larger. While some states have traditional maps with such level of detail, others are investing in lidar and/or photogrammetric surveys to update their geospatial databases. Photogrammetric DEMs with resolution of 2 m are available for the states of Espírito Santo<sup>4</sup> and Santa Catarina<sup>5</sup>, while

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<sup>1</sup><https://www.usgs.gov/3d-elevation-program> - Last access 2025-07-15

<sup>2</sup>Value calculated using the Digital Index Map (4th edition, 2011), based on the ‘available’ (*disponíveis*) topographic maps ([direct download link](#))

<sup>3</sup><https://bdgex.eb.mil.br/bdgexapp> - Last access 2025-07-15

<sup>4</sup><https://geobases.es.gov.br> - Last access 2025-07-15

<sup>5</sup><https://sigsc.sc.gov.br/> - Last access 2025-07-15

Bahia<sup>6</sup> and Amapá<sup>7</sup> have partial state coverage of 5 m DEMs from airborne InSAR (the same system used by the RAM project). São Paulo offers 5 m DSM and DTM for the whole state, although these are interpolated from photogrammetrically-derived point heights with 15 m spacing, and present numerous issues, such as interpolation artifacts and surface texture mismatch between adjacent tiles. Pernambuco was the first state to provide open DSMs and DTMs from lidar surveys<sup>8</sup>, with 1 m resolution (Cirilo *et al.*, 2014). Most of the state capitals (and other large cities) have lidar surveys, but do not distribute the data for lack of digital infrastructure to host and serve large amounts of data. The city of São Paulo, the most populous city in the country (and fourth in the world, with  $\approx 11,450,000$  inhabitants), serves two lidar surveys (2017 and 2020) through the city’s geoportal, GeoSampa<sup>9</sup>. The data is distributed as point clouds in LAS format. Grohmann & Gomes (2022) created a DSM and a DTM from the 2017 data and hosted them on Kaggle.

The Geographical and Cartographic Institute of São Paulo (IGC-SP – *Instituto Geográfico e Cartográfico*) the official cartographic agency of the São Paulo State coordinate a project to map the entire state area with lidar. The surveys happened between 2023 and 2024. The point clouds have a minimum point density of 10 pts/m<sup>2</sup> in the Metropolitan Region of São Paulo (the city of São Paulo and its neighboring cities) and of 4 pts/m<sup>2</sup> in the rest of the state.

In the night of 18-19th February 2023, a massive rainfall event struck the northern shore of São Paulo State (Fig.1A). In the city of São Sebastião, a precipitation of more than 600 mm in 24h led to widespread landslides, floods and localized debris flows, causing 65 casualties and major infrastructure damage; in the neighboring Ilhabela, the rainfall reached 337 mm and affected mainly its southern region, triggering landslides detectable in aerial imagery on more elevated hillsides (Marengo *et al.*, 2024).

An inventory of the São Sebastião landslides was produced by Coelho *et al.* (2024) (Fig.1B), based on a 10 cm resolution orthomosaic released by the São Paulo State Government only a few days after the disaster (Fig.1C). The inventory contains 1,070 landslide scar polygons. Bonini *et al.* (2025) created a landslide inventory for the same area using object-based Random Forest algorithm, identifying 396 scars in São Sebastião and 100 in Ilhabela.

Efforts to prevent future disasters in the region include improving landslide susceptibility maps for the area. Landslide susceptibility analysis intends to recognize the conditions in which past landslides occurred, and employ that information to determine where new events might happen (Aleotti & Chowdhury, 1999; Guzzetti *et al.*, 2012). A review of such studies in Brazil by Dias *et al.* (2021) revealed that DEMs are widely used to derive land-surface parameters (LSPs – slope, aspect, curvatures, etc) used as input for susceptibility models. Given the scarcity of high-resolution open elevation data in Brazil, researchers resort to global DEMs like SRTM or CopDEM. For example, Varnier (2024) used NASADEM and Random Forest within Google Earth Engine to evaluate landslide susceptibility for the municipalities of São Sebastião and Ilhabela, mapping 5.4% of the area as highly susceptible. Alcântara *et al.* (2024) used a weighted sum model to develop susceptibility maps for four climate scenarios from the Intergovernmental Panel on Climate Change (IPCC), but did not specify the source of the elevation data. While the resolution of  $\approx 30$  m might be enough for regional-scale analysis, it lacks the angular coherence between neighboring pixels necessary to derive LSPs for detailed studies (Hengl, 2006; Valeriano *et al.*, 2006; Grohmann *et al.*, 2007). Moreover, each pixel represents an area of  $\approx 900$  m<sup>2</sup>, which can be larger than entire small landslides.

To properly study landslide susceptibility on a local scale, lidar data are the best option. If data is acquired before a landslide event, DTMs with 1–5 m resolution can faithfully represent the topography and derived LSPs. In the case of post-event surveys, one can calculate the difference between the DSM and the DTM, to highlight the scars and deposit areas.

After negotiations with the IGC-SP, our research group obtained access to the raw lidar data

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<sup>6</sup> Accessible via the Brazilian Army BDGEx Portal

<sup>7</sup> <https://sema.portal.ap.gov.br> - Last access 2025-07-15

<sup>8</sup> <https://pe3d.pe.gov.br/> - Last access 2025-07-15

<sup>9</sup> <https://geosampa.prefeitura.sp.gov.br/> - Last access 2025-07-15



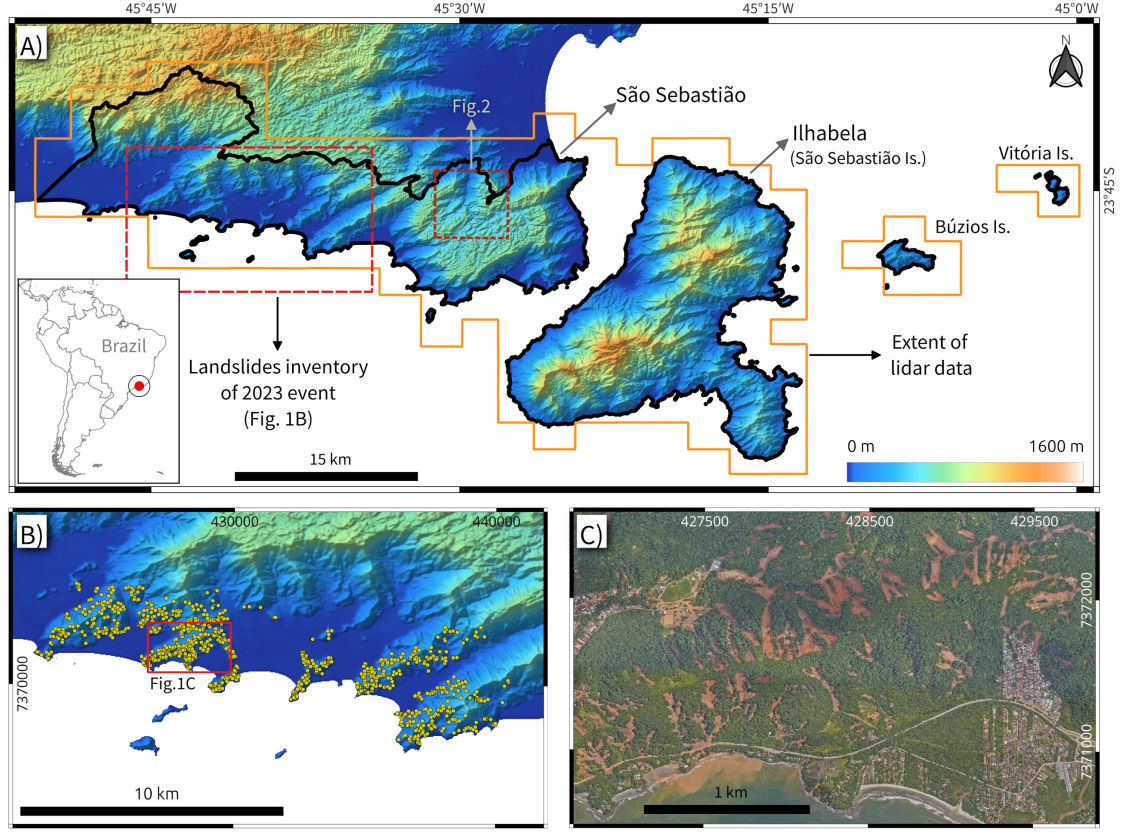


Figure 1: A) Location and morphological context of São Sebastião and Ilhabela municipalities, southeastern Brazil. The thick black line marks the cities' boundaries. Orange line show the limits of lidar data. Terrain morphology from FABDEM (Hawker *et al.*, 2022). Insets (red dashed line), delimits the area of the landslides inventory by Coelho *et al.* (2024) (shown in B) and of Figure 2. B) Landslide inventory for the 2023 event (Coelho *et al.*, 2024). C) Orthophoto of the landslides, surveyed on 2023-02-25 by the São Paulo State Government (IDE-SP, 2023).

for São Sebastião and Ilhabela, in order to produce landslide susceptibility maps based on a high-resolution DTM, and to provide technical feedback to IGC-SP on the quality of the data. Although raw data cannot be shared, derivative products, such as DEMs and LSPs, can. Therefore, following the principles of Open Science (OECD, 2015), in this paper we describe a high-resolution dataset of elevation and land-surface parameters derived from the lidar data. We understand these data are invaluable not only to academic researchers studying the region, but also to policymakers and the Public Administration.

## 2. Data and Methods

The data used in this study consist of raw airborne lidar point cloud files in LAS format, totaling approximately 650 GB of data. The data cover the entire area of the municipalities of São Sebastião and Ilhabela (Fig. 1).

The LAS files follow the ASPRS LAS 1.4 specification (ASPRS, 2011) and include standard point attributes such as XYZ coordinates, intensity, return number, number of returns, classification, and GPS time. All data are provided in the WGS 84 / UTM zone 23S coordinate reference system (EPSG:32723). Point classification encompasses ground, low/medium/high vegetation, and buildings. The ground point density varies across acquisition blocks, with an average of 0.32 points per square meter, ensuring sufficient detail to generate digital terrain models with a grid spacing of 2 m (Anderson *et al.*, 2006; Hengl, 2006).

All data processing and analysis steps were performed using a combination of open-source and proprietary tools. Specifically, we employed the WhiteboxTools (WbT) and Whitebox Workflows (WbW) libraries (Lindsay, 2016) for lidar data processing and terrain analysis. The task ‘smooth vegetation residual’ was performed using Whitebox Workflows Professional, the commercial version of the Whitebox suite, which offers extended functionality for point cloud manipulation and surface modeling.

### 2.1. Lidar Data Processing and DTM Generation

The lidar data processing workflow consisted of five main stages: ground point filtering, merging of filtered files, DTM generation via TIN interpolation, gap filling in the DTM, and subsequent surface smoothing (Table 1). All raster outputs at each stage were exported in compressed TIFF format to optimize storage and ensure compatibility with subsequent analyses. Throughout the workflow, file/object existence checks and systematic memory management were applied to enhance computational efficiency and guarantee reproducibility.

Table 1: Whitebox tools and parameters for each step of the lidar processing workflow applied to the DTM generation.

Step	Description	WbW Tool	Main Parameters
Step 1	Ground point filtering	<code>filter_lidar_classes</code>	<code>exclusion_classes = [1, 3–19]</code>
Step 2	Merging filtered LAS files	<code>lidar_join</code>	Region-specific files merged
Step 3	TIN interpolation	<code>lidar_tin_gridding</code>	<code>cell_size = 2 m</code> , <code>max_triangle_edge = 1,000 m</code>
Step 4	Filling DTM gaps	<code>fill_missing_data</code>	<code>filter_size = 51</code> , <code>weight = 2.0</code> , <code>exclude edges</code>
Step 5a	Remove off-terrain objects (Lindsay, 2018)	<code>remove_off_terrain_objects</code>	<code>filter_size = 7</code> , <code>slope_threshold = 11.0</code>
Step 5b	Smooth vegetation residual (WbW Pro)	<code>smooth_vegetation_residual</code>	<code>max_scale = 15</code> , <code>dev_threshold = 0.06</code> , <code>scale_threshold = 4</code> (2 passes)
Step 5c	Feature-preserving smoothing (Lindsay <i>et al.</i> , 2019a)	<code>feature_preserving_smoothing</code>	<code>filter_size = 3</code> , <code>normal_diff_threshold = 12.0</code> , <code>iterations = 1</code>

### 2.2. Land-surface parameters and objects

Land-surface parameters (LSPs) and land-surface objects (LSOs) are the two DEM-derived entities fundamental to modern geomorphometry (Mark & Smith, 2004; Pike *et al.*, 2009). An LSP is a descriptive and quantitative measure of surface characteristics, such as slope, aspect, and curvatures. An LSO is a discrete spatial feature, such as a drainage network, ridge, or watershed lines. We provide a set of 17 LSPs and LSOs, that comprise several facets of the landscape, including illumination, shape, landform characteristics, and hydrology.

Figure 2 shows an example of three LSPs (hillshade, slope and surface roughness) for the 2 m lidar DTM (Fig. 2 A/B/C), a 5 m photogrammetric DTM from IDE-SP (Fig. 2 D/E/F), and the 30 m FABDEM DTM (Fig. 2 G/H/I). The area is almost completely covered by dense forests, and was selected to illustrate not only the effectiveness of our processing workflow, providing a clean surface while preserving the sharpness of ridgelines, but also some issues with the other datasets. The 5 m DTM has a clear north-south division in two areas with contrasting texture, indicating poor vegetation filtering. FABDEM shows an issue often overlooked by DEM users, linear artifacts



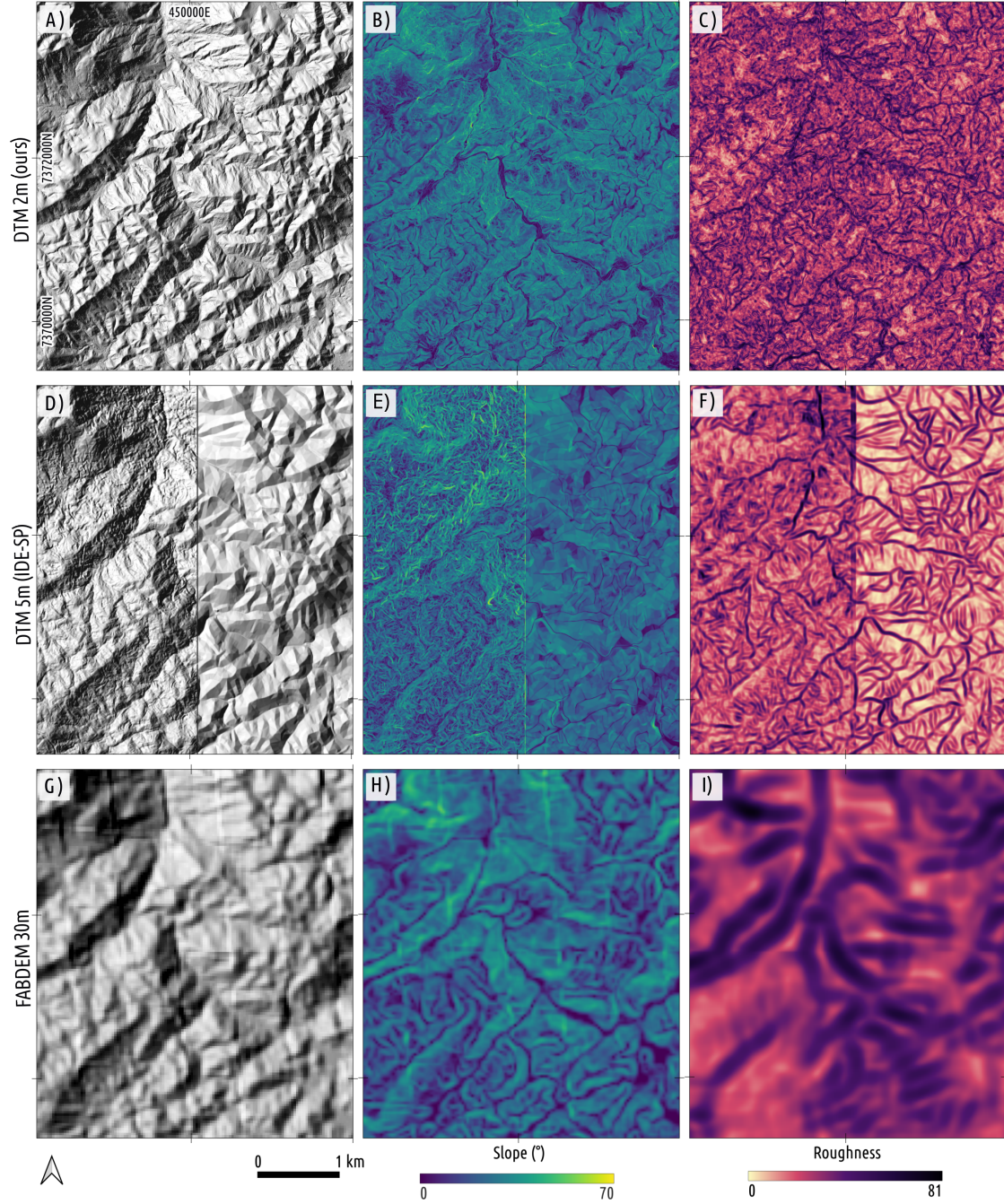


Figure 2: Comparison of terrain parameters derived from high-resolution (DTM 2 m), intermediate resolution (DTM 5 m from IDE-SP), and coarse resolution (FABDEM 30 m) DEMs for the study area. Location of area shown in Fig. 1. A/D/G: Hillshade. B/E/H: Slope. C/F/I: Surface roughness.

caused by cell size adjustment due to projection from Lat-Long to UTM (Grohmann & Steiner, 2008).

**Hillshade**, or shaded relief, is a technique of terrain visualization considering the orientation of a light source and the local slope and aspect (Horn, 1981; Imhof, 1982). We used the tool `multidirectional_hillshade`, and set altitude to  $30^\circ$ , and Z-factor to 1 as default.

**Slope** steepness was calculated with the `slope` tool, with the output in degrees. Since the

data are in a projected coordinate system, this tool uses a polynomial fit of the elevations within the 5x5 neighborhood surrounding each cell (Florinsky, 2016).

**Aspect**, the slope orientation in degrees clockwise from north, was calculated with the `aspect` tool, using a 5x5 neighborhood of each cell (Florinsky, 2016).

**Profile Curvature** is the rate of change in slope along a flow line, and characterizes the degree of downslope acceleration or deceleration (Gallant & Wilson, 2000). Profile curvature is negative for slope increasing downhill (convex) and positive for slope decreasing downhill (concave). We used the tool `profile_curvature`, with output in units of  $m^{-1}$ .

**Plan Curvature** (or contour curvature), is the rate of change in aspect along a contour line, and characterizes the degree of flow convergence or divergence within the landscape (Gallant & Wilson, 2000). Plan curvature is negative for diverging flow and positive for convergent areas. We used the tool `plan_curvature`, with output in units of  $m^{-1}$ .

**Minimal Curvature** is the curvature of a principal section with the lowest value of curvature at a given point of the topography (Florinsky, 2017). Positive values correspond to hills while negative values correspond to valley positions (Florinsky, 2016). We used the tool `minimal_curvature`, with output in units of  $m^{-1}$ , and set the `log_transform` option to `True`.

**Maximal Curvature** is the curvature of a principal section with the highest value of curvature at a given point of the topography (Florinsky, 2017). Positive values correspond to ridges while negative values indicate closed depressions (Florinsky, 2016). We used the tool `maximal_curvature`, with output in units of  $m^{-1}$ , and set the `log_transform` option to `True`.

**Difference from Mean Elevation** is the difference between the elevation of each grid cell and the mean elevation of its local neighborhood, being a measurement of relative topographic position. We used the tool `difference_from_mean_elevation`, and set `filterx` and `filtery` to 11 grid cells.

**Shape Index** (Koenderink & van Doorn, 1992) is a dimensionless variable ranging from -1 to 1, useful for landform classification. Positive values indicate convex landforms, and negative values correspond to concave landforms (Florinsky, 2017). Absolute values from 0.0 to 0.5 are characteristic of hyperbolic forms (saddles), while absolute values from 0.5 to 1.0 are associated with elliptic forms (hills and closed depressions). We used the tool `shape_index`, which requires a license for Whitebox Workflows for Python Professional.

The **Geomorphons** landform classification is based on a line-of-sight analysis for the eight topographic profiles in the cardinal directions surrounding each grid cell of the input DEM (Jasiewicz & Stepinski, 2013). We used the `geomorphons` tool with default parameters.

**Spherical Standard Deviation of Normals** measures the angular dispersion of the surface normal vectors within a local neighborhood, being a measure of *surface roughness*, complexity, and texture (Grohmann *et al.*, 2011; Lindsay *et al.*, 2019b). We used the tool `spherical_std_dev_of_normals`, and set `filter_size` to 11 grid cells.

**Flow Accumulation** was calculated with the multiple-flow-direction (MFD) algorithm from (Qin *et al.*, 2007). The DTM was pre-processed with the `breach_depressions_least_cost` tool (Lindsay & Dhun, 2015) with the `max_dist` set to 900 m. We then used the `qin_flow_accumulation` tool, with `out_type` set to `sca` (specific contributing area – the catchment area divided by the flow width), and `log_transform` set to `False`.

**Wetness Index** describes the tendency for a site to be saturated to the surface, given its contributing area and local slope characteristics. This raster was calculated with the `wetness_index` tool, using the flow accumulation and slope rasters as inputs.

**Flow Direction** is commonly used as input for other spatial hydrology and stream network analysis. In the Whitebox suite, this is calculated with the `d8_pointer` tool, which is based on the D8 algorithm (O’Callaghan & Mark, 1984).

A **Stream network** can be derived from a DEM based on a flow accumulation raster and a specified threshold, which represents the minimum area required to initiate and maintain a channel. We used the `extract_streams` tool with the flow accumulation raster as input and the `threshold` set to 4000 for São Sebastião and 1500 for Ilhabela.

### 3. Topographic features of interest

Upon inspection of the DTM and derived LSPs, several interesting topographic features were identified, including evidence of past large landslide deposits, river captures and subvolcanic landforms. A selection of examples is shown in Figure 3.

Past landslides indications are highlighted in profile curvature maps by convex and concave landform patterns. Figure 3A shows colluvial deposits from past landslides just north of Vila Sahy, an area heavily affect by the event of 2023. A relic landslide scarp is visible in Fig. 3D, to the west of Castelhanos Beach in Ilhabela.

A drainage capture is shown in Fig. 3B, where a small drainage bends abruptly (indicated by a white arrow) before flowing south from the plateau. Over the plateau a trellis drainage pattern is observed, indicating a structural control over the stream network. Large tectonic lineaments are seen in Fig. 3C: an E-W lineament is marked by black arrows, and a curvilinear structure is indicated by white arrows.

In Fig. 3E, the slope map highlights concentric circular ridges of the Serraria Stock, which is part of the 88-85 Ma alkaline plutonic event of the Serra do Mar Province (Sato, 2006; Sato *et al.*, 2008; Giraldo-Arroyave *et al.*, 2021). In Fig. 3F, a flat-bottomed depression is visible in a surface roughness map, just north of Indaiaúba Beach; this depression is not clearly identifiable in optical imagery due to dense forest cover.

### 4. Conclusions

This study presents the first publicly available high-resolution Digital Terrain Model (i.e., ‘bare-earth’) and a comprehensive set of land-surface parameters (LSPs) for the municipalities of São Sebastião and Ilhabela, southeastern Brazil, derived from airborne lidar data. The 2 m-resolution DTM significantly enhances the representation of topographic features when compared to existing regional and global elevation datasets, allowing the identification of subtle geomorphological structures relevant to landslide susceptibility assessment and environmental studies. By providing an open-access dataset processed with a transparent and reproducible workflow, this work contributes to filling a critical gap in Brazil’s high-resolution topographic data availability, promoting applications that range from scientific research to disaster risk management and territorial planning. Future work should explore the integration of this dataset with multitemporal remote sensing products and climate projections to refine hazard models and support adaptive strategies in vulnerable mountainous regions.



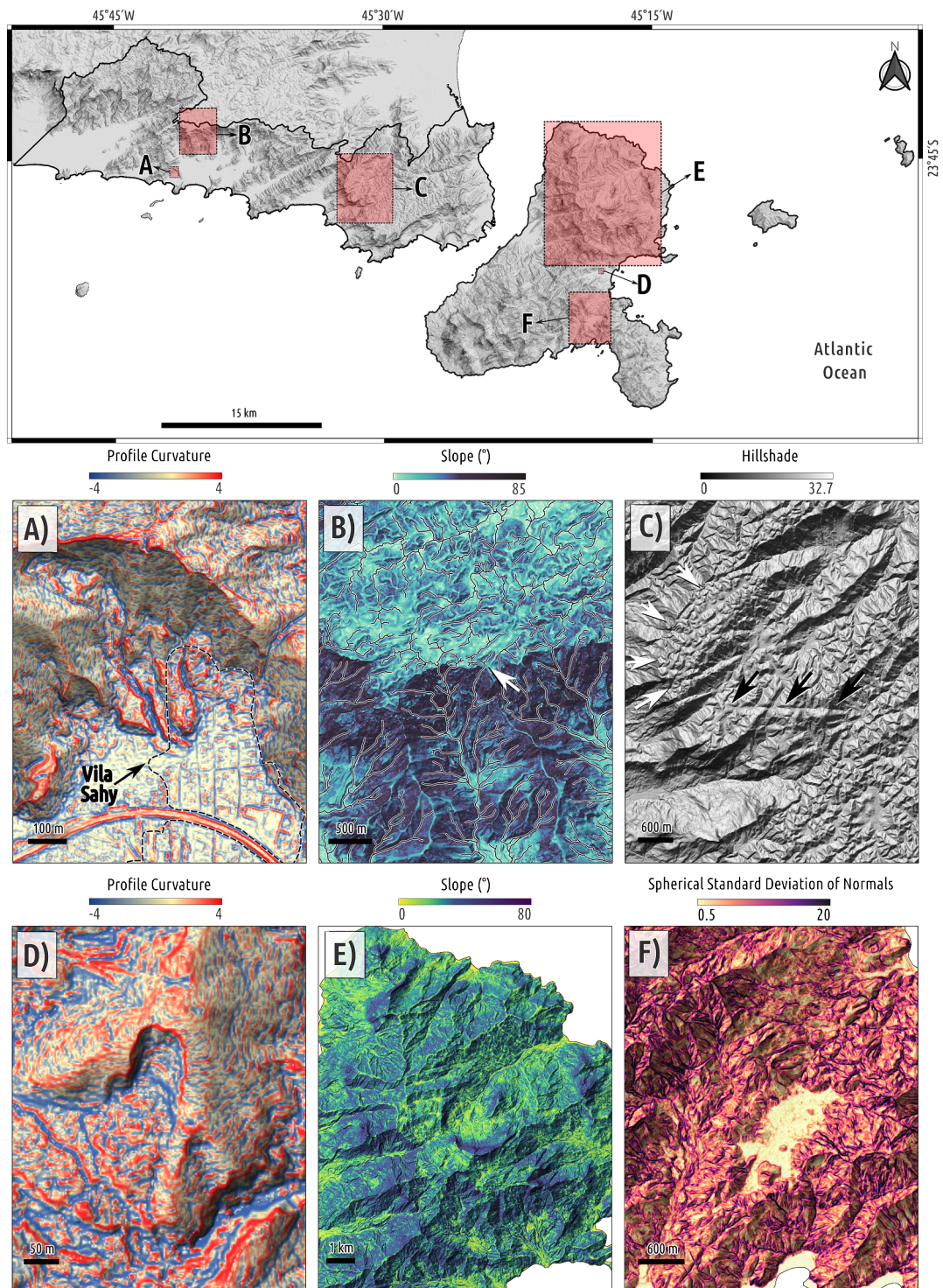


Figure 3: Examples of relevant topographic features identified within the study area, based on different terrain variables derived from the Digital Terrain Model (DTM). A) Deposits of past landslides in the Vila Sahy region, highlighted by convex and concave landform patterns; B) Drainage capture at the transition between the plateau and the escarpment (indicated by the white arrow); C) Structural lineaments revealed by variations in terrain illumination (black and white arrows); D) Scarp of a past landslide with a prominent colluvial deposit downslope; E) Concentric circular ridges, associated with subvolcanic alkaline plutonism; F) Flat-bottom depression evidenced by low surface roughness compared to the surrounding area.

## 5. Dataset Reference

Coelho, R.D., Frugis, G.L., Viana, C.D., Grohmann, C.H., 2025. High-resolution Digital Terrain Model and Land-surface Parameters of São Sebastião, southeastern Brazil. *Zenodo*. DOI: <http://dx.doi.org/10.5281/zenodo.16903678>

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